

**Woods Hole
Oceanographic
Institution**



**Monthly Maps of Sea Surface Height in the North Atlantic
and Zonal Indices for the Gulf Stream Using
TOPEX/Poseidon Altimeter Data**

by

Sandipa Singh and Kathryn A. Kelly

June 1997

Technical Report

Funding was provided by the National Aeronautics and Space Administration through
Contract Nos. NAGW-1666 and NAGW-4806.

Approved for public release; distribution unlimited.

19970808 019

Monthly Maps of Sea Surface
Height in the North Atlantic and
Zonal Indices for the Gulf Stream
Using TOPEX/Poseidon Altimeter
Data

Sandipa Singh
Kathryn A. Kelly

Woods Hole Oceanographic Institution
Woods Hole, MA

Abstract

Monthly maps of sea surface height are constructed for the North Atlantic ocean using *TOPEX/Poseidon* altimeter data. Mean sea surface height is reconstructed using a weighted combination of historical, hydrographic data and a synthetic mean obtained by fitting a Gaussian model of the Gulf Stream jet to altimeter data. The resultant mean shows increased resolution over the hydrographic mean, and incorporates recirculation information that is absent in the synthetic mean. Monthly maps, obtained by adding the mean field to altimeter sea surface height residuals, are used to derive a set of zonal indices that describe the annual cycle of meandering as well as position and strength of the Gulf Stream.

CONTENTS

Contents

1	Introduction	6
2	Reconstructing the Mean Sea Surface Height	6
2.1	Obtaining the hydrographic mean	6
2.2	Obtaining a synthetic mean	6
2.3	Combining the hydrographic and the synthetic means	8
2.4	Obtaining Monthly Sea Surface Height Maps	11
3	Calculating Gulf Stream Indices	13
	Acknowledgements	15
	References	20
	Appendix	21

LIST OF FIGURES

List of Figures

1	TOPEX/Poseidon ascending ground track coverage	7
2	TOPEX/Poseidon descending ground track coverage	7
3	Dynamic height from historical hydrographic data	8
4	Synthetic <i>ssh</i> mean obtained from TOPEX/Poseidon data.	9
5	A comparison of total height, HydroBase height and net height along subtrack 226.	10
6	Initial sampling pattern, interpolated subtracks, and final grid	10
7	Weights used on the synthetic mean.	11
8	Weighted combination of HydroBase and synthetic means.	12
9	Error function fit to height along 50°W for November 1994.	13
10	Path of the Gulf Stream jet	14
11	Zonal indices for 73°W to 64°W from TOPEX/Poseidon	16
12	Zonal indices for 73°W to 64°W from Geosat	17
13	Zonal indices for 63°W to 50°W from TOPEX/Poseidon	18
14	Zonal indices for 63°W to 50°W from Geosat	19

2 RECONSTRUCTING THE MEAN SEA SURFACE HEIGHT

1 Introduction

This report describes the construction of monthly maps of total sea surface height (*ssh*) in the North Atlantic ocean using *TOPEX/Poseidon* altimeter data. These maps are then used to derive zonal indices that describe the transport, position, velocity, and curvature of the Gulf Stream.

Collinear analysis of the subtrack data is described extensively in [1]. The end-product of this analysis is cleaned residual *ssh* profiles splined along-track on to a common latitude grid. Since the mean is removed along with the geoid in the collinear analysis, it is first necessary to recover the mean height field in order to measure total *ssh* difference. The first section of this report deals with the reconstruction of a mean for the North Atlantic using both historical hydrographic data and a synthetic mean derived using the Kelly/Gille/Qiu method [4], [5]. This mean is used along with the *ssh* residuals to obtain monthly maps of *ssh*. The second section describes the calculation of zonal indices that characterize the state of the Gulf Stream (GS) from these monthly maps. Contour plots of the monthly maps are included in the Appendix.

2 Reconstructing the Mean Sea Surface Height

For the purposes of this study, the subtracks that fell between latitudes 20°N to 60°N and longitudes 30°W to 80°W were analyzed for cycles 4 through 80 which spanned a time period from October 1992 to November 1994. Cycles one through three were discarded because of poor data quality. Figures 1 and 2 show the coverage of ascending and descending ground tracks in this area along with the *ssh* variance along the tracks. The peak of the variance reveals the position of the GS jet.

Two separate calculations of the mean are described in the following subsections.

2.1 Obtaining the hydrographic mean

To obtain a climatological mean, we used the Lozier/Owens/Curry HydroBase data set which calculates the mean dynamic height by gridding raw, historical data for pressure, temperature and salinity on density surfaces [3]. This yields netCDF files which are then used to extract the dynamic height of the surface relative to a reference depth of 2000 meters. Figure 3 shows a contour plot of these data.

2.2 Obtaining a synthetic mean

To generate a synthetic mean using the Kelly/Gille/Qiu method, the Gulf Stream velocity was modeled as a Gaussian jet [4]. Assuming that the GS meanders a distance

2 RECONSTRUCTING THE MEAN SEA SURFACE HEIGHT

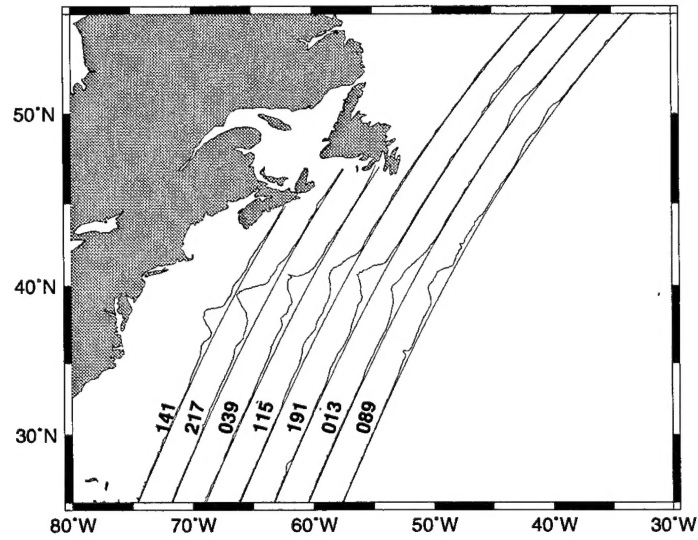


Figure 1: *TOPEX/Poseidon* ascending ground track coverage for the North Atlantic showing *ssh* variance along track.

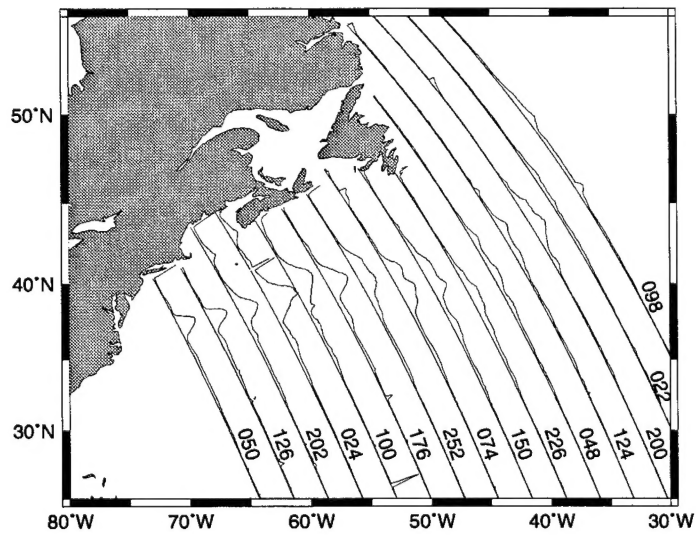


Figure 2: *TOPEX/Poseidon* descending ground track coverage for the North Atlantic showing *ssh* variance along track.

2 RECONSTRUCTING THE MEAN SEA SURFACE HEIGHT

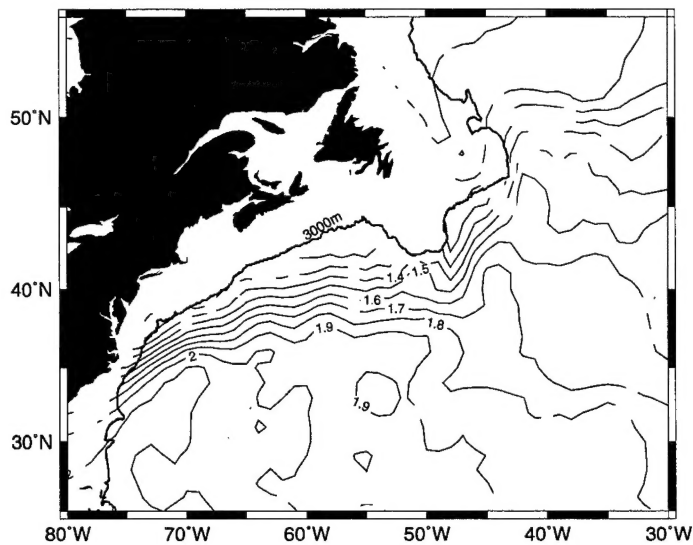


Figure 3: Dynamic height from historical hydrographic data, reference level 2000 meters.

at least as large as its width, the instantaneous *ssh* residuals will contain information on the magnitude and position of the jet. These, combined with an initial guess of the mean strength, define the Gaussian velocity jet completely. A least squares fit to the Gaussian jet was performed on the *ssh* residuals for each subtrack and the parameters of the fit modified until a convergence criterion was satisfied. This method was applied to all tracks independently and yielded a mean *ssh* field (Figure 4) that was consistent in position, but with a narrower and stronger GS than that obtained from hydrographic data.

2.3 Combining the hydrographic and the synthetic means

The Kelly/Gille/Qiu synthetic method only models the jet and cannot be used to recover the mean far from the GS itself. In other words, there is no information about the recirculation gyres that can be seen in the HydroBase mean. To incorporate information away from the GS while retaining the narrower width of the jet, the simple Gaussian jet model was modified. If we assume that the difference in height between the synthetic and the HydroBase mean is due to the presence of northern and southern recirculation gyres in the latter, then the recirculation gyres can be modelled as a wide, slow Gaussian jet, whose height equals this difference (Figure 5). For this model, first mean height profiles of hydrographic data were obtained by splining gridded HydroBase data along satellite subtracks. An error function fit was performed on the profiles which yielded the function,

2 RECONSTRUCTING THE MEAN SEA SURFACE HEIGHT

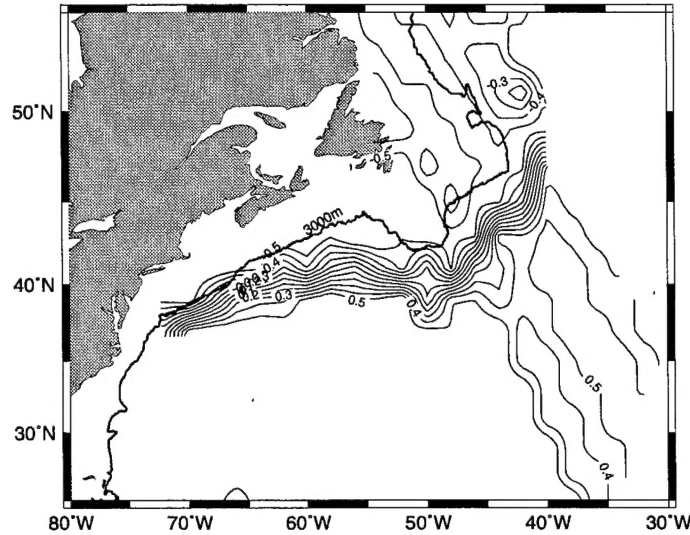


Figure 4: Synthetic *ssh* mean obtained from *TOPEX/Poseidon* data.

$erf(a_1, a_2, a_3)$, where a_1, a_2, a_3 are the amplitude, position and width parameters of the fit. The recirculation was then set to an error function $erf(a_1 - a_1^s, a_2, 2a_3)$, where a_1^s is the amplitude parameter of the synthetic mean height profile. This recirculation error function was subtracted from the synthetic mean profiles to yield modified synthetic profiles.

Finally, the modified synthetic profiles were gridded to $1^\circ \times 1^\circ$ and combined with the HydroBase mean using a spatially varying function. The profiles were first interpolated between tracks to retain the narrow jet structure of the Gulf Stream and then splined onto the $1^\circ \times 1^\circ$ grid using a biharmonic spline. The interpolation could be carried out since the mean height did not change much from track to track (except in the bifurcation region around $50^\circ W$). Figure 6 shows the spacing of the original tracks as thick solid lines, the interpolated ones are thin lines, and the open circles are the $1^\circ \times 1^\circ$ grid points.

The weighting function used for combining the HydroBase mean with the gridded mean was calculated by low-pass filtering the magnitude of the gradient of *ssh* of the synthetic mean (Figure 7). This procedure weighted the synthetic mean more heavily in regions of large velocities where the Gaussian model is expected to be more accurate, and the hydrographic mean more heavily away from the Gulf Stream, where the Gaussian model is not accurate. East of $40^\circ W$, where there was no synthetic mean data, the HydroBase mean was used exclusively, whereas inside the 3000 meter isobath, where no HydroBase data are available, the synthetic mean was used. The resulting map is shown

2 RECONSTRUCTING THE MEAN SEA SURFACE HEIGHT

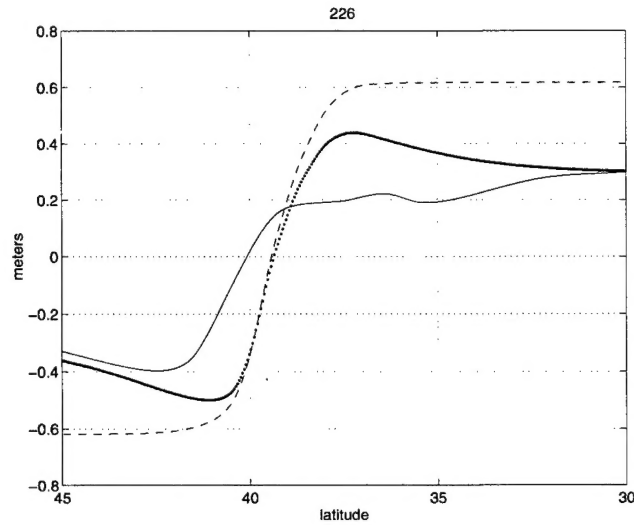


Figure 5: A comparison of total height (dashed line), HydroBase height (light line) and net height (heavy line) along subtrack 226.

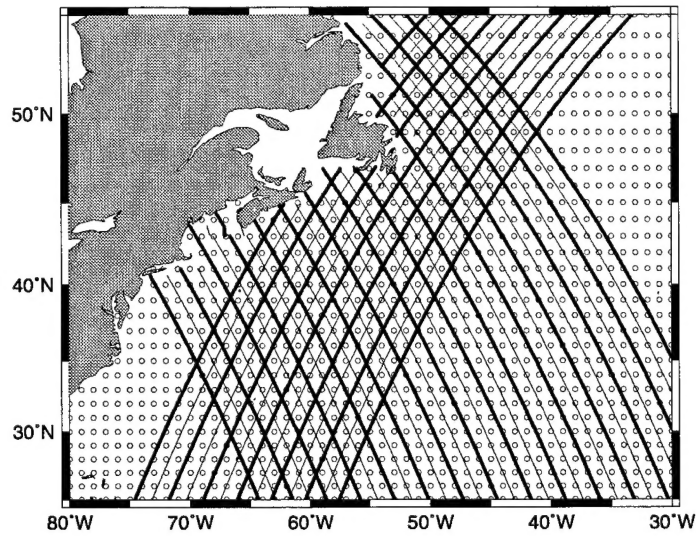


Figure 6: Heavy subtrack lines mark the initial sampling pattern of the mean height, light lines show the interpolated subtracks and circles indicate the final grid onto which it was mapped.

2 RECONSTRUCTING THE MEAN SEA SURFACE HEIGHT

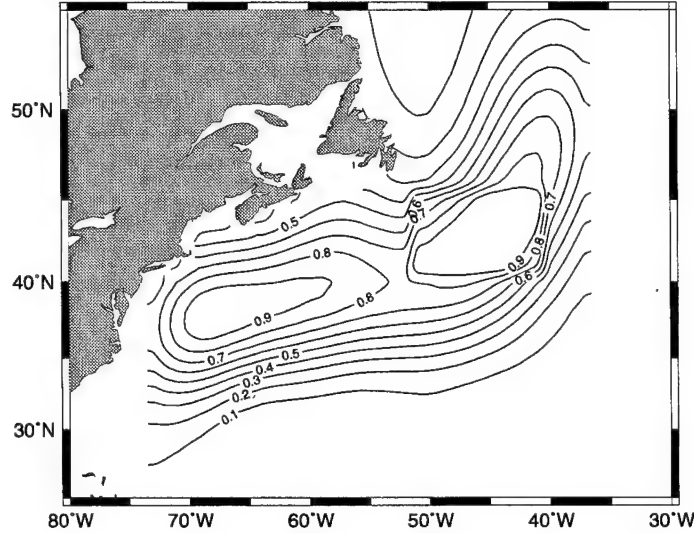


Figure 7: Weights used on the synthetic mean.

in Figure 8. The combined mean field shows increased resolution over the hydrographic mean, and incorporates recirculation information which could not previously be obtained from the synthetic method.

2.4 Obtaining Monthly Sea Surface Height Maps

Mean *ssh* field reconstructed in the previous step can now be added back to the *ssh* residuals to obtain monthly maps of the Gulf Stream and the North Atlantic Current. For this, the residuals need to be regridded in both time and space. Assuming that the two are independent, the two-dimensional regridding can be broken up into two separate one-dimensional problems. The residuals are first averaged in time using a boxcar filter with a width of sixty days. This puts all cycles on a monthly spacing. The monthly cycles are then splined on to a 1° by 1° grid using a two-dimensional biharmonic spline. They are then added to the means. See the Appendix for contour plots of the monthly maps so obtained.

Monthly maps derived from the earlier *Geosat* mission were also included in this study and covered a period from November 1986 to April 1989. *Geosat* subtrack data have an across-track spacing approximately half that of the *TOPEX/Poseidon* data, with a longer sampling period of 17 days. It was processed similarly but had an orbit correction applied to it [2]. Because of smaller across-track spacing, it was gridded on to a $0.5^\circ \times 0.5^\circ$ grid. Mean sea surface height was constructed by combining the synthetic

2 RECONSTRUCTING THE MEAN SEA SURFACE HEIGHT

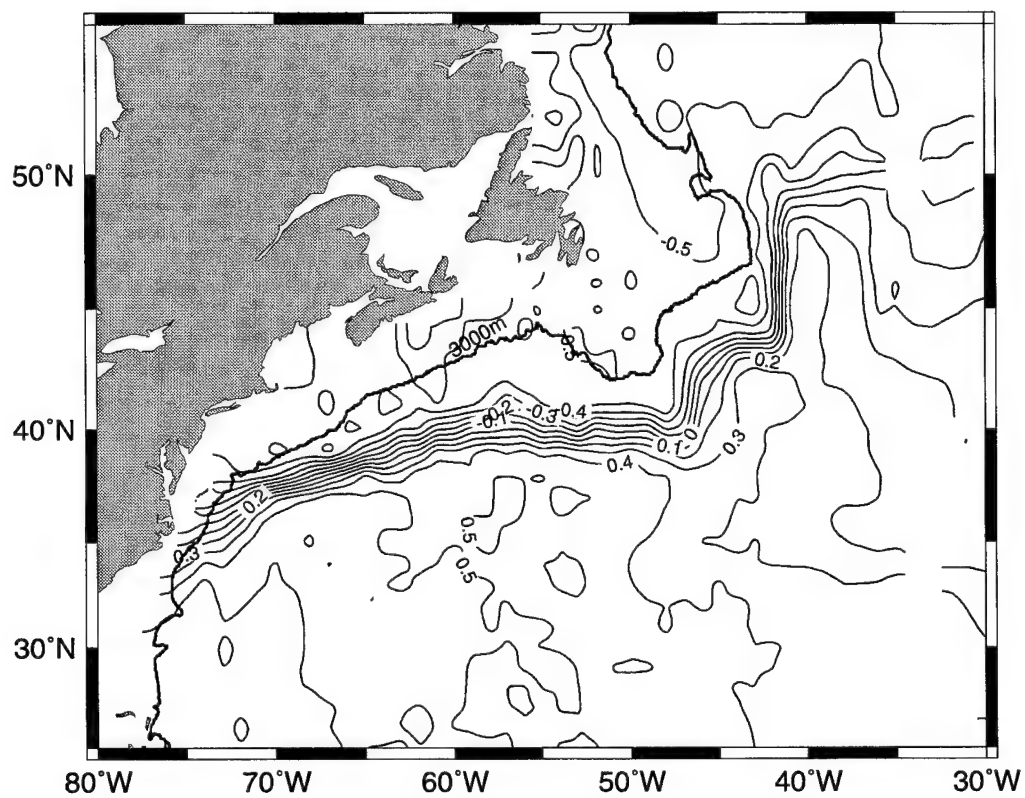


Figure 8: Weighted combination of HydroBase and synthetic means.

3 CALCULATING GULF STREAM INDICES

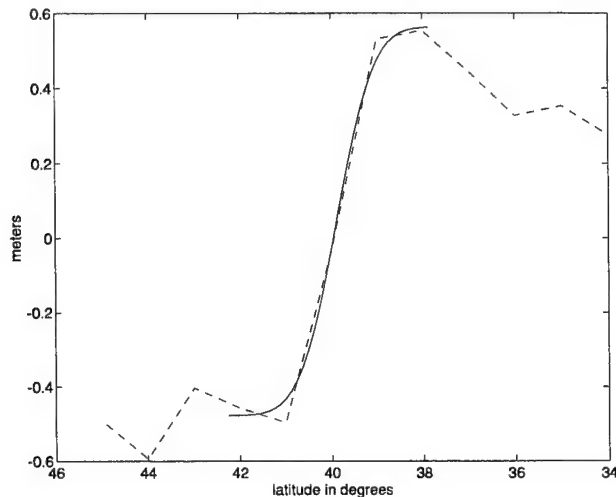


Figure 9: Error function fit to height along 50°W for November 1994.

mean with historical hydrographic data [6].

3 Calculating Gulf Stream Indices

To characterize the annual cycle of meandering, as well as the strength and position of the Gulf Stream, a series of zonal indices were developed from monthly maps of *ssh*. These indices covered a region from 73°W to 50°W which was further broken down into two subregions: upstream and downstream of 63°W, the approximate location of the New England Seamounts. The calculation of each index is enumerated below:

1. Transport: Height profiles along each degree of longitude are interpolated onto a 0.125 degree grid, and error functions are then fitted to them to estimate height difference across the jet. Figure 9 shows a fit for one profile. These height differences are averaged over all longitudes to get the height difference index for the month.
2. Position: If the path of the Gulf Stream is described by the zero contour of the height field, the mean position, P , is just a zonal average of the latitude of this zero contour. To get a robust estimate of path, the -0.1, 0 and 0.1 meter contours are averaged (Figure 10) before calculating P .

3 CALCULATING GULF STREAM INDICES

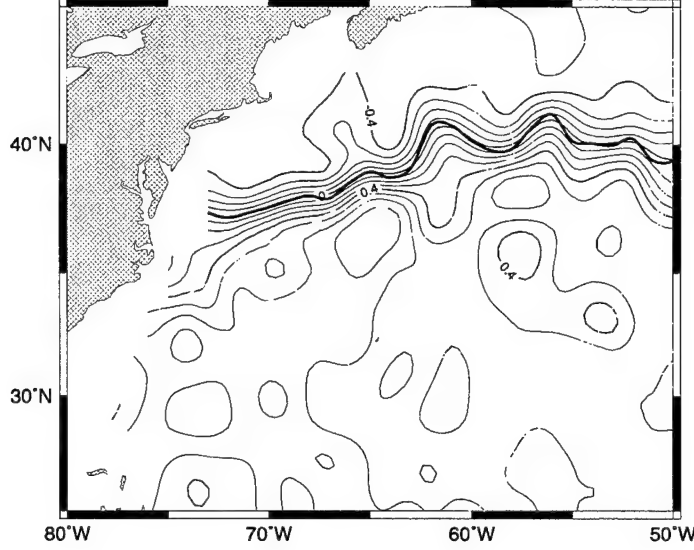


Figure 10: Path of the Gulf Stream jet (heavy black line) for November 1994, overlaid on *ssh* contours for that month. Slight differences in the path from the height contours are due to the different plotting packages used to create them.

3. Curvature: Curvature of a function $y = f(x)$ is given by:

$$C = \frac{y''}{[1 + (y')^2]^{3/2}} \quad (1)$$

where the primes denote differentiation with respect to x . In this case, f is the path of the Gulf Stream as described in the calculation of P , x is the longitude of the path while y is the latitude. Curvature is calculated at every point along the path, and is then averaged across the path to yield the curvature index, C .

4. Eastward Velocity: Eastward velocity is calculated along each degree of longitude. Since peak velocity estimates may be noisy, the velocity at a fixed width of one degree is used as the eastward velocity of the jet. This is averaged for all longitudes to yield the velocity index, V .

The above four indices were calculated for both the *TOPEX/Poseidon* as well as the *Geosat* monthly maps. *Geosat* derived monthly maps were decimated to a $1^\circ \times 1^\circ$ grid and GS indices were calculated similarly except for the position index, which was calculated using the center of the error function used for the *ssh* difference. This

3 CALCULATING GULF STREAM INDICES

was because of differences in the way the mean field was reconstructed in the two data sets as well as differences in spatial resolution. Figures 11 and 12 show the indices for *TOPEX/Poseidon* and *Geosat* for the upstream region (73°W to 64°W), while Figures 13 and 14 show the indices for the downstream region (63°W to 50°W). Although there is no clear annual cycle apparent in the downstream indices, there is one in the upstream ones. Putting together both time series and fitting an annual signal to them shows a maximum in position (corresponding to a minimum in curvature) in September with a minimum (and a corresponding maximum in curvature) in March. Transport is maximum in October and minimum in April. The amplitudes of the position and transport indices are 0.21° and 0.07m respectively. This implies that the Gulf Stream is stronger and follows a relatively straight and northerly path in fall, and then shifts to a southerly position with weaker transport accompanied by more meandering in spring. A detailed analysis of the index cycle may be found in [7].

Acknowledgements

Support for this project was provided by NASA under contracts NAGW-1666 and NAGW-4806.

3 CALCULATING GULF STREAM INDICES

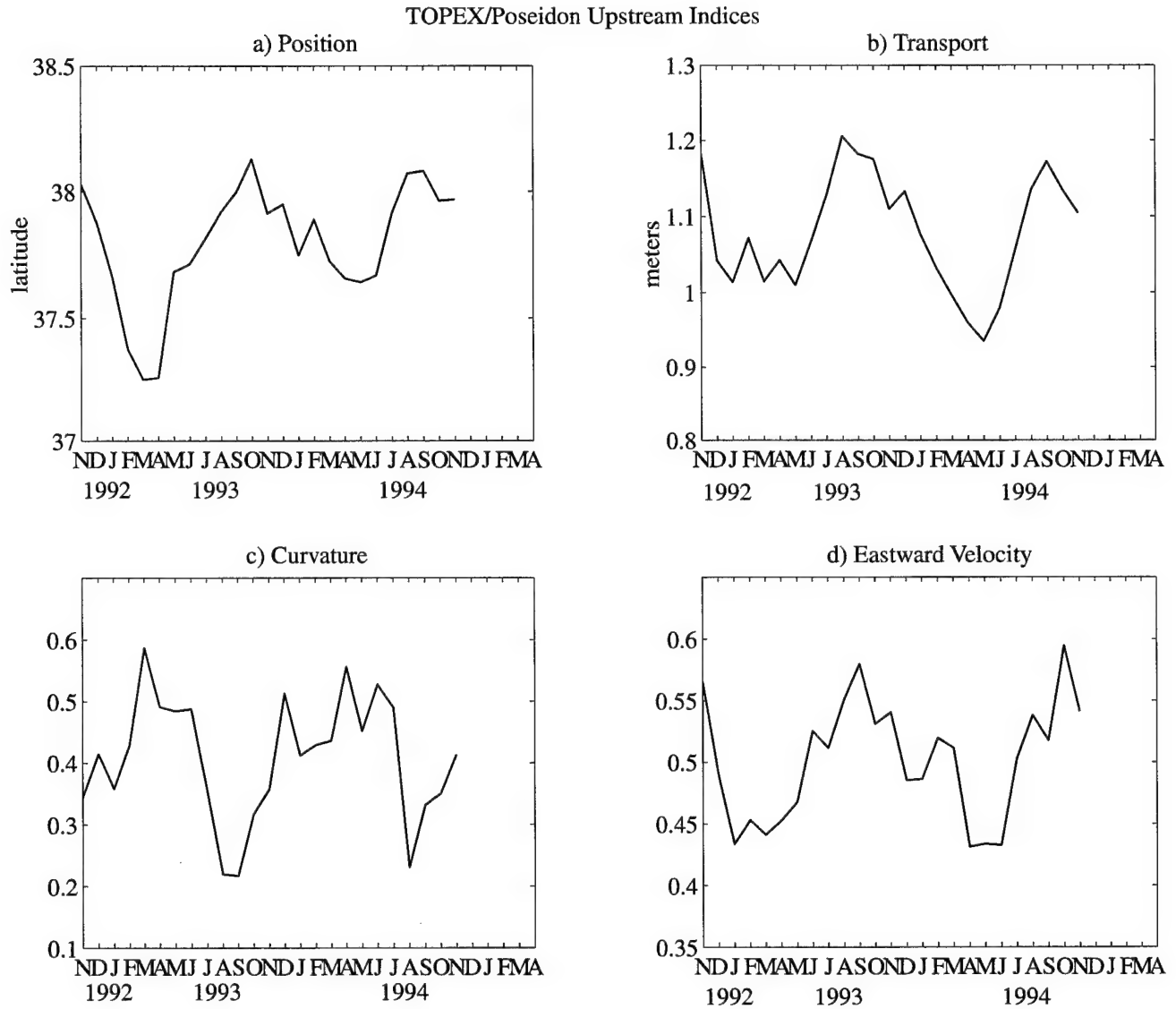


Figure 11: Zonal indices for 73°W to 64°W from *TOPEX/Poseidon*.

3 CALCULATING GULF STREAM INDICES

Geosat Upstream Indices

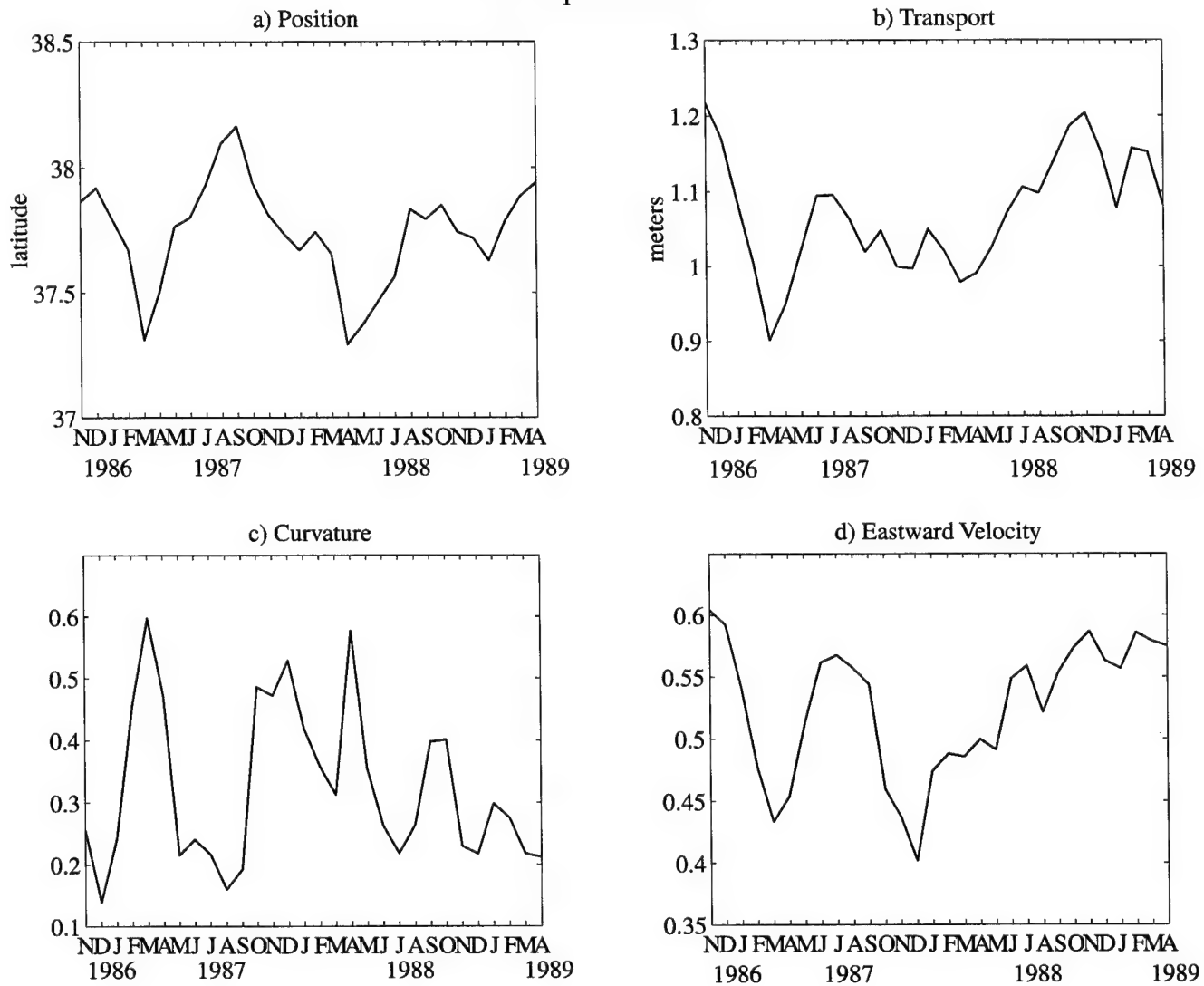


Figure 12: Zonal indices for 73°W to 64°W from *Geosat*.

3 CALCULATING GULF STREAM INDICES

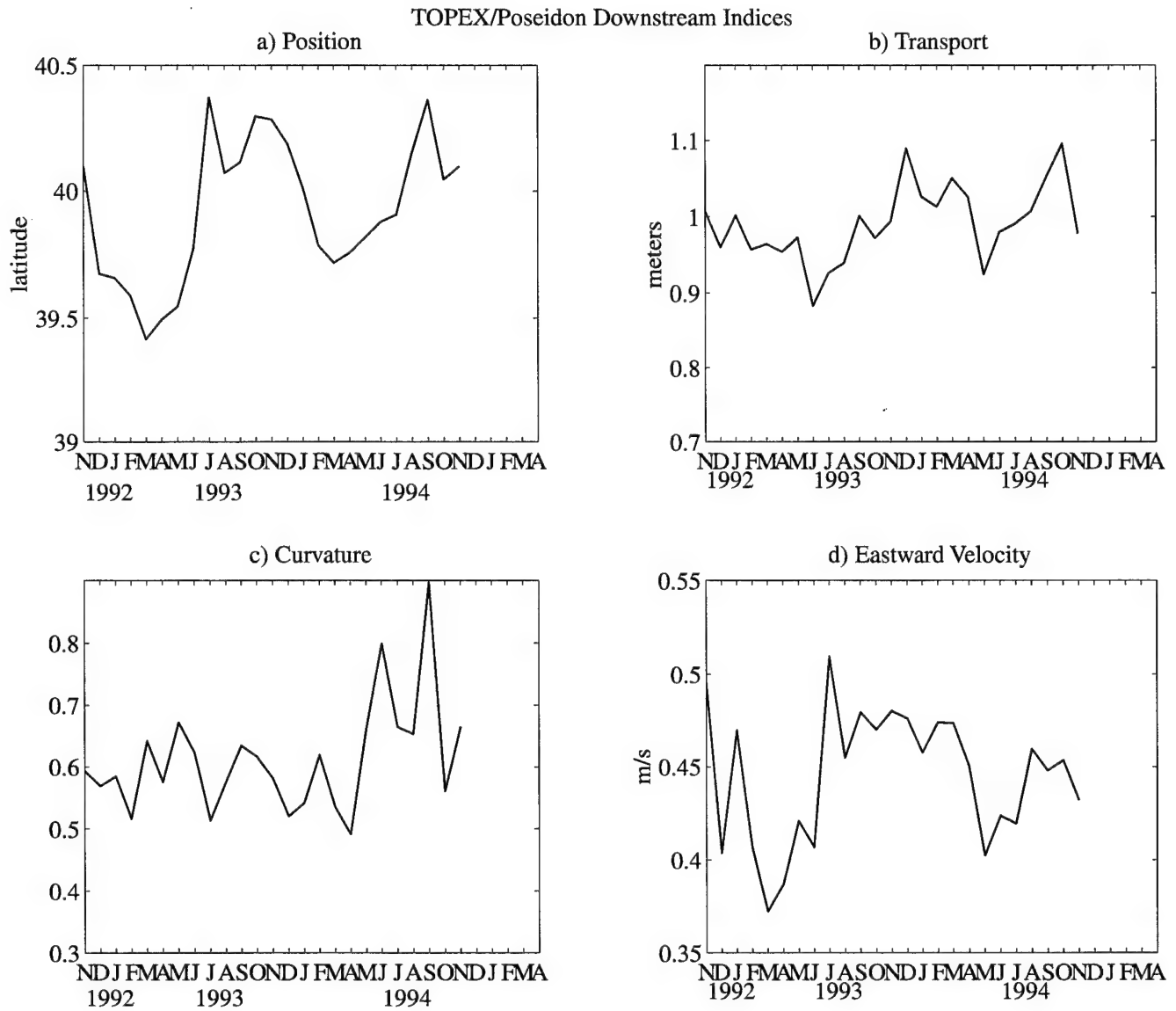


Figure 13: Zonal indices for 63°W to 50°W from *TOPEX/Poseidon*.

3 CALCULATING GULF STREAM INDICES

Geosat Downstream Indices

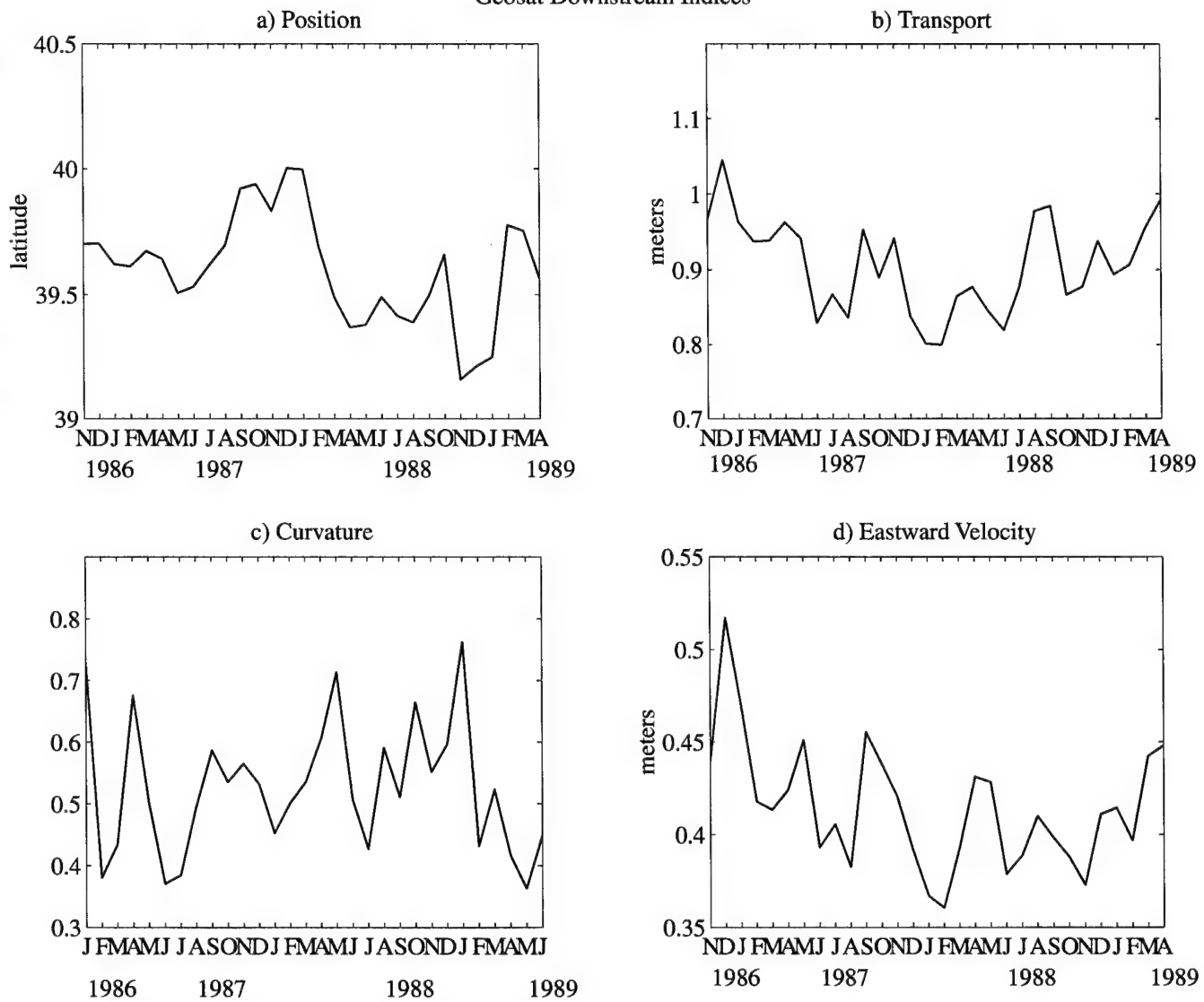


Figure 14: Zonal indices for 63°W to 50°W from *Geosat*.

REFERENCES

References

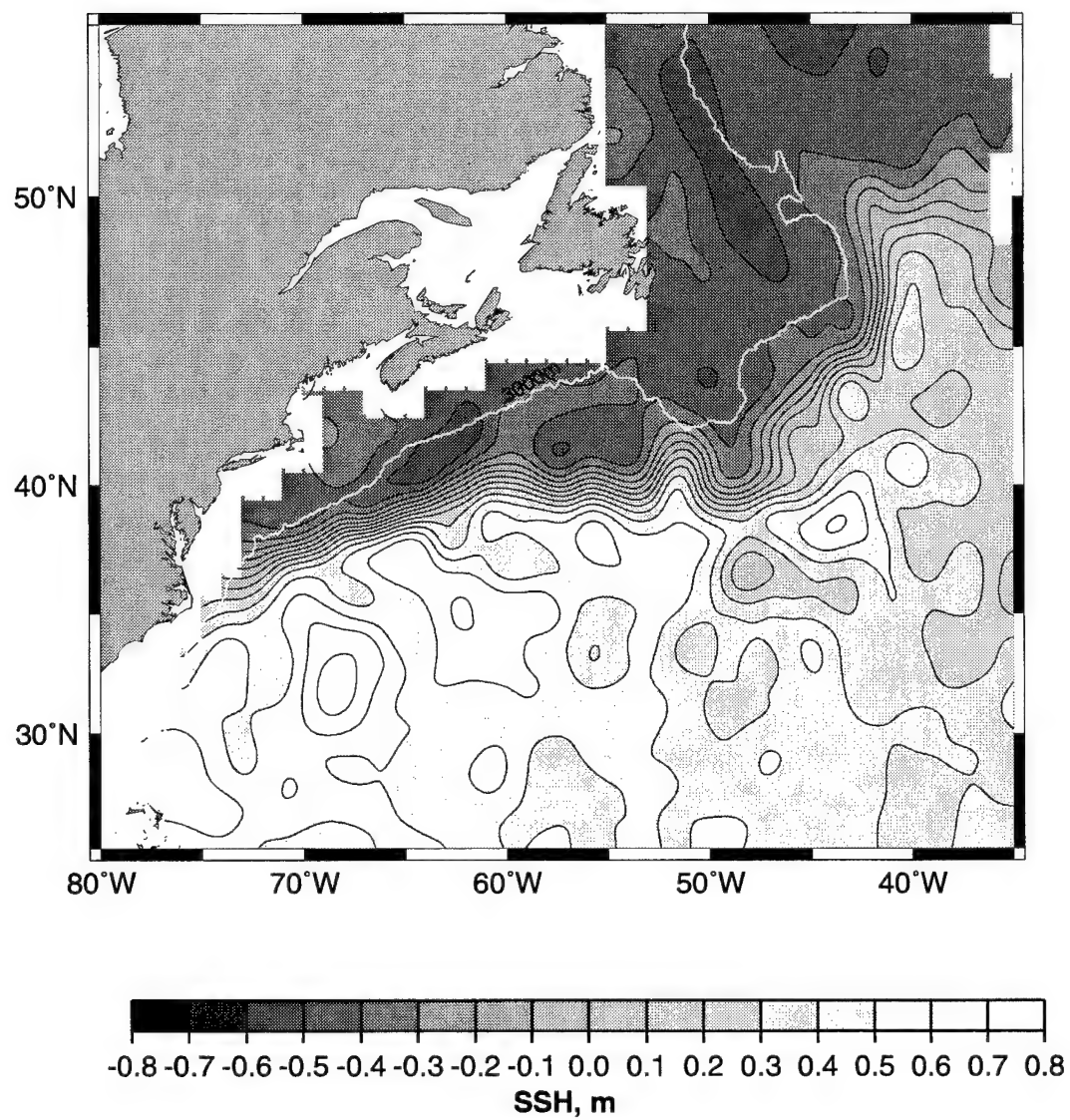
- [1] Caruso, M. C., S. Singh, and K. A. Kelly, **TOPEX/Poseidon** altimeter data processing in the North Atlantic, Tech. Rept., Woods Hole Oceanogr. Inst. *in preparation*.
- [2] Caruso, M. C., S. Singh, K. A. Kelly and B. Qiu, 1995. Monthly atmospheric and oceanographic surface fields for the western North Atlantic: October, 1986 – April, 1989. *Tech. Rept., WHOI-95-05*, Woods Hole Oceanogr. Inst., Woods Hole, Mass., 75 pp.
- [3] Curry, R. G., 1996. HydroBase: A Database of hydrographic stations and tools for climatological analysis. *Tech. Rept. 96-01*, Woods Hole Oceanogr. Inst., Woods Hole, Mass., 50 pp
- [4] Kelly, K. A., and S. T. Gille, 1990. Gulf Stream surface transport and statistics at 69° W from the GEOSAT altimeter, *J. Geophys. Res.* **95**, 3149–3161.
- [5] Qiu, B., K. A. Kelly and T. M. Joyce, 1991. Mean circulation and variability of the Kuroshio Extension from Geosat altimetry data. *J. Geophys. Res.*, **96**, 18,491–18,507.
- [6] Qiu, B., 1994. Determining the mean Gulf Stream and its recirculations through combining hydrographic and altimetric data, *J. Geophys. Res.*, **99**, 951–962.
- [7] Kelly, K. A., S. Singh and R. X. Huang. The index cycle in the Gulf Stream. *in preparation*

Appendix

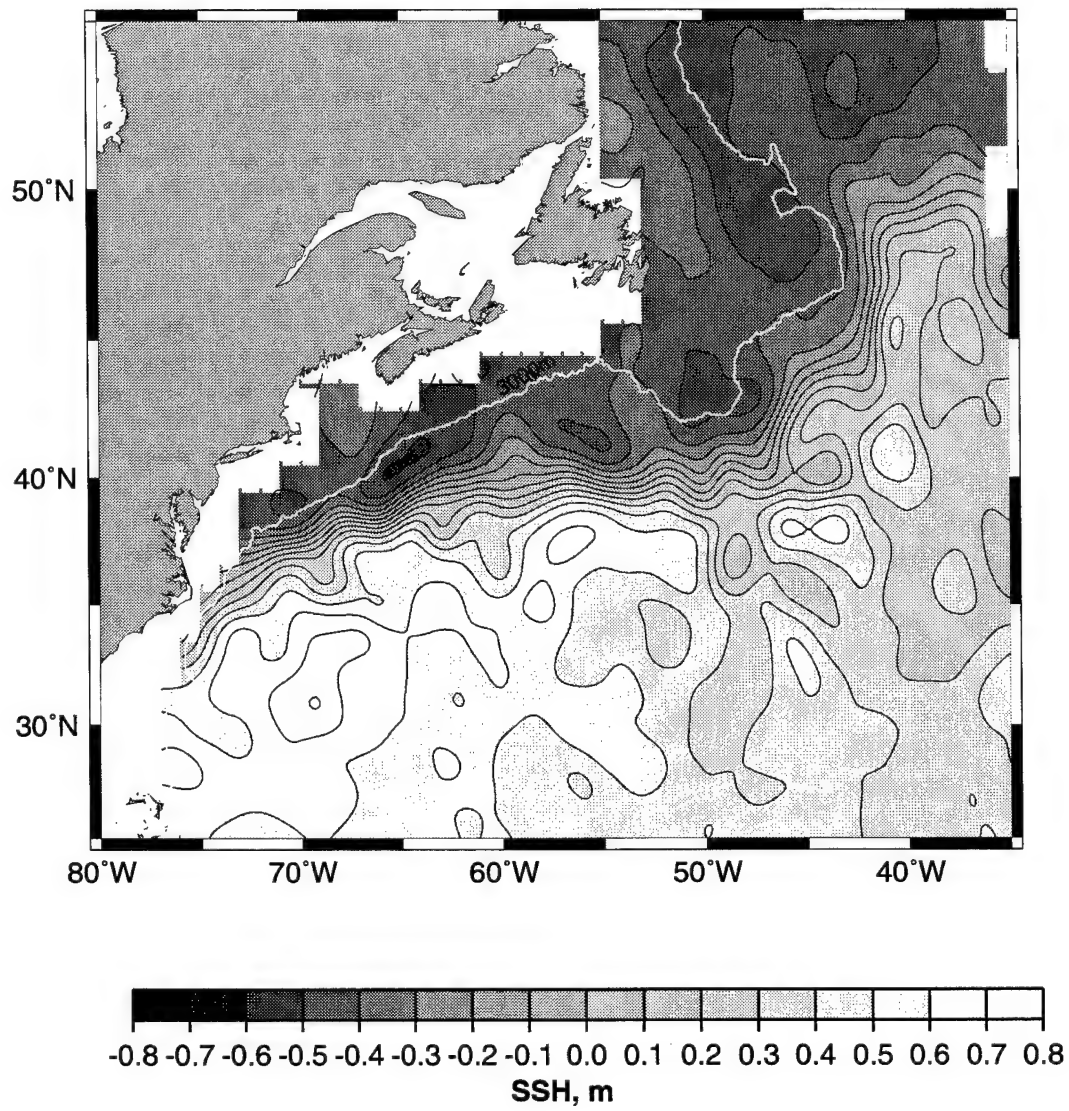
Monthly maps of total *ssh* derived from *TOPEX/Poseidon* altimeter data are included for the period from November 1992 to November 1994. The 3000 meter isobath (white contour line) is included in the maps for reference.

APPENDIX

November 92

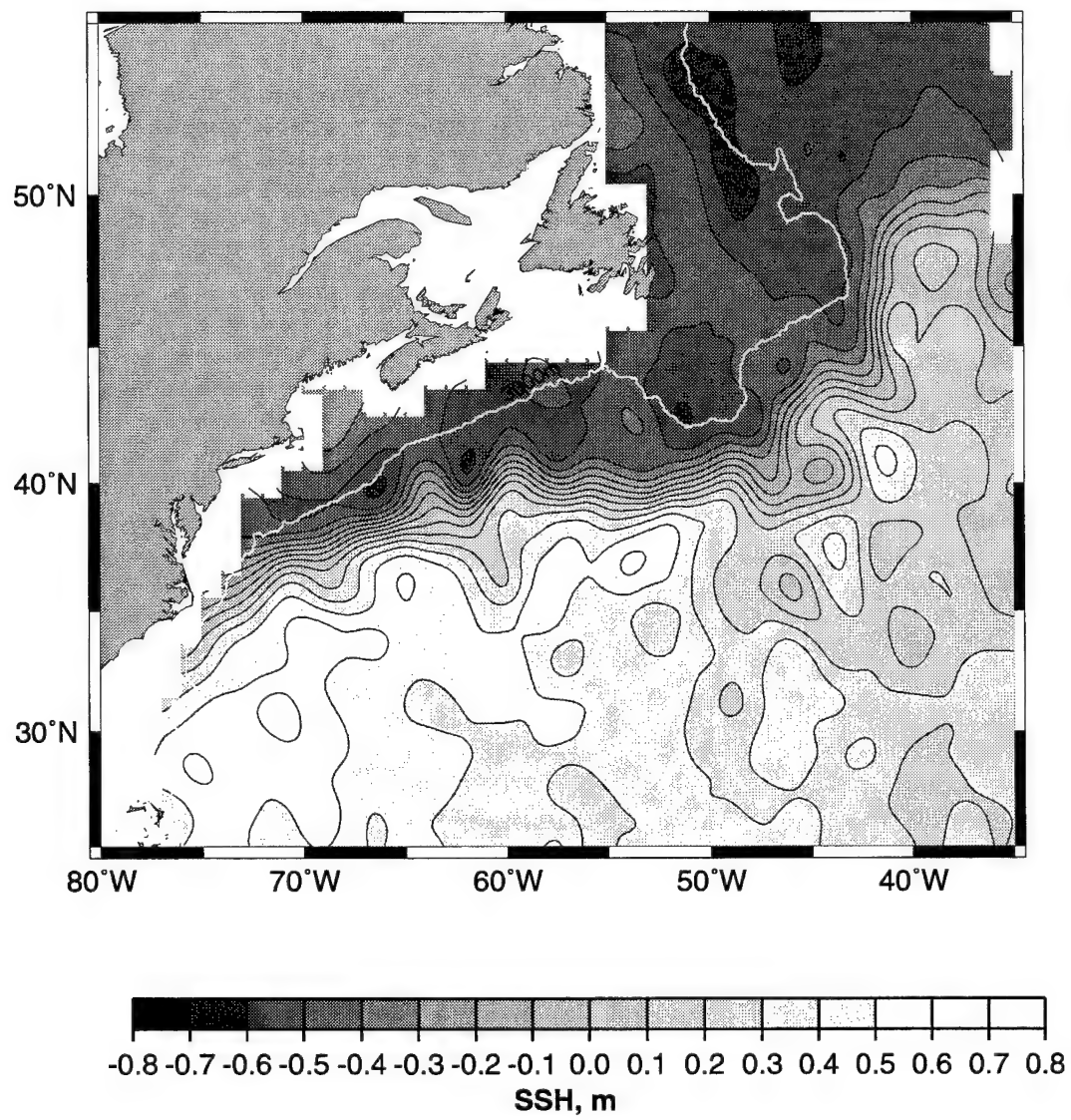


December 92

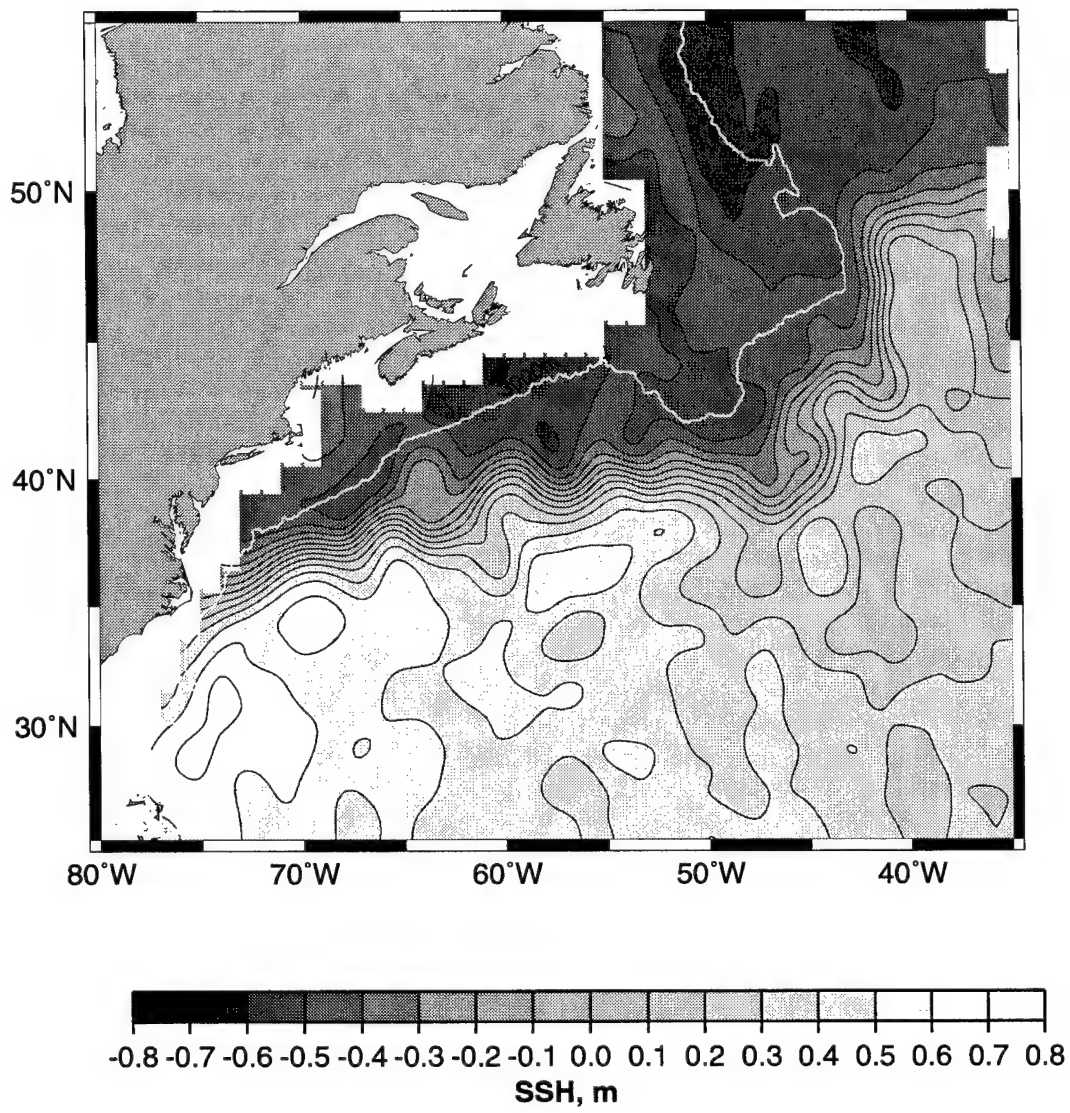


APPENDIX

January 93

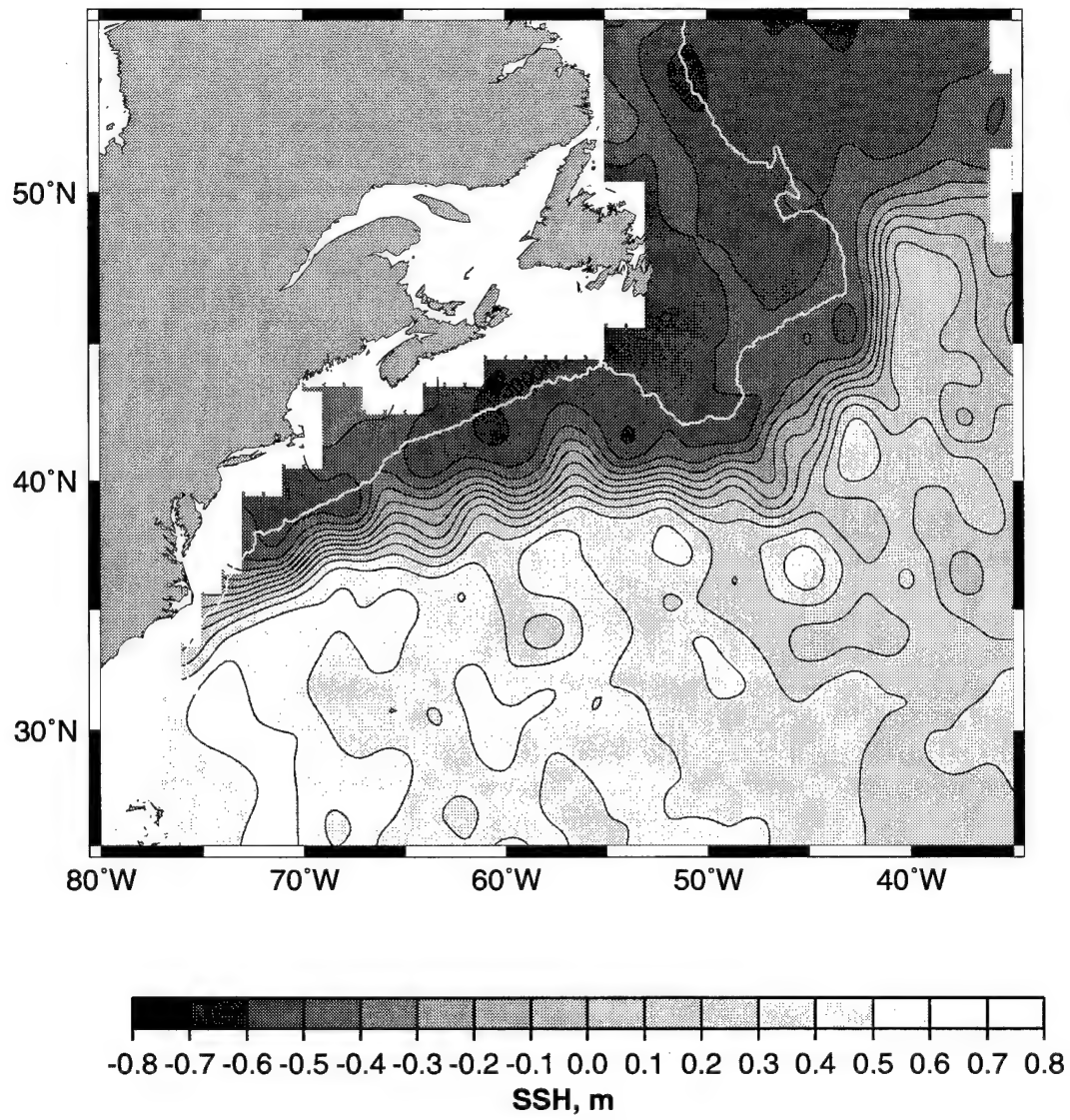


February 93

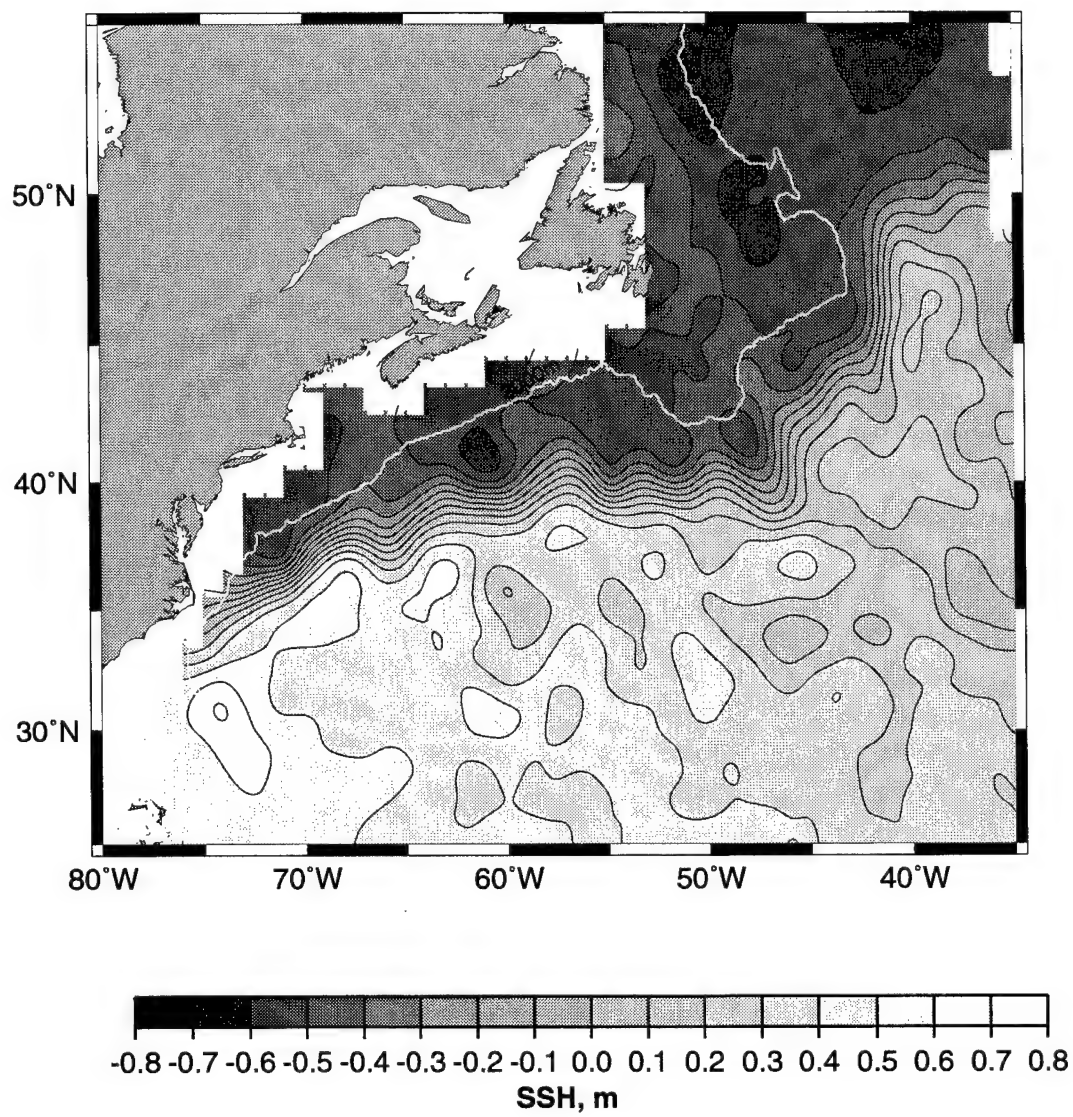


APPENDIX

March 93

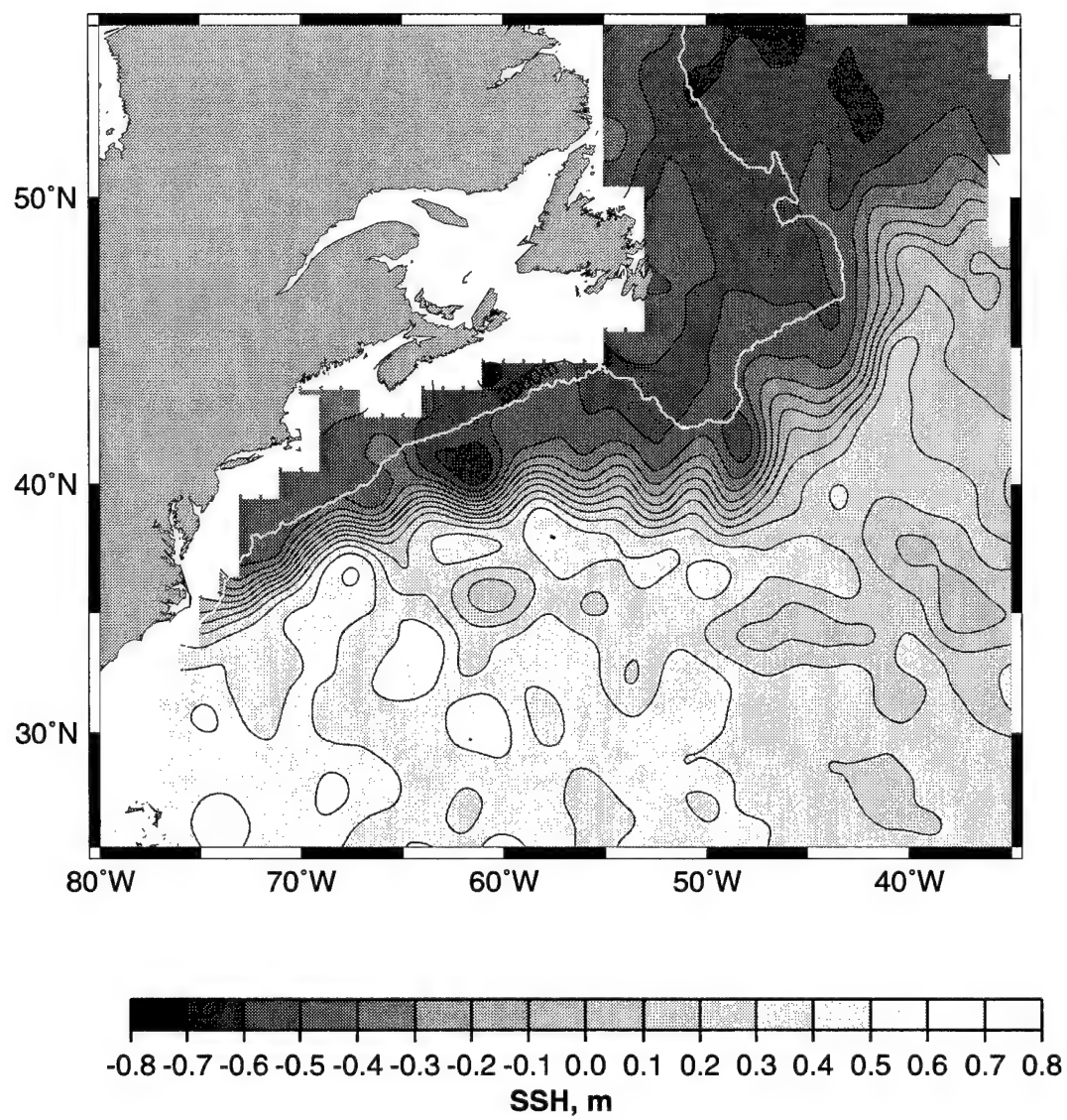


April 93

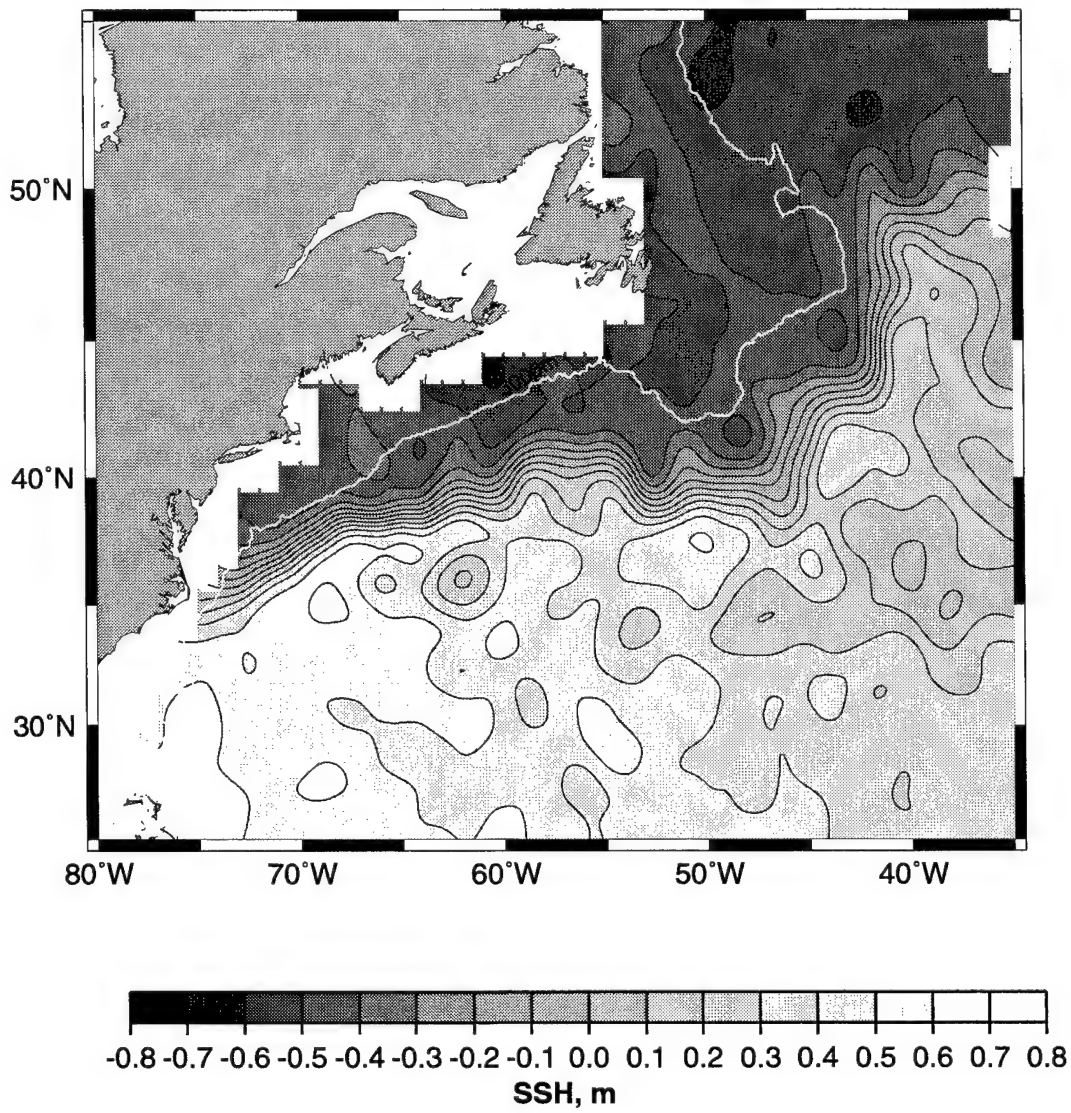


APPENDIX

May 93

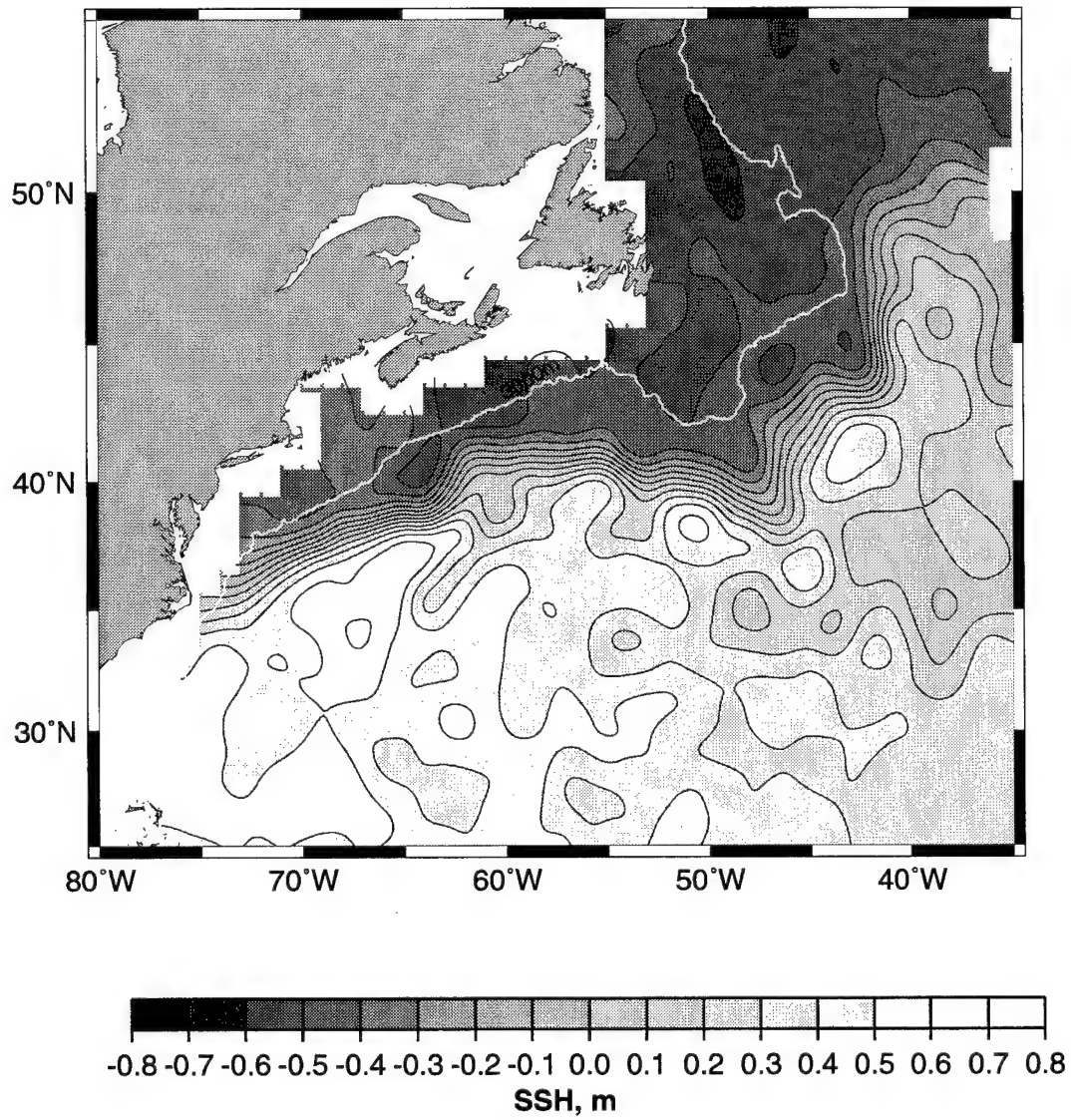


June 93

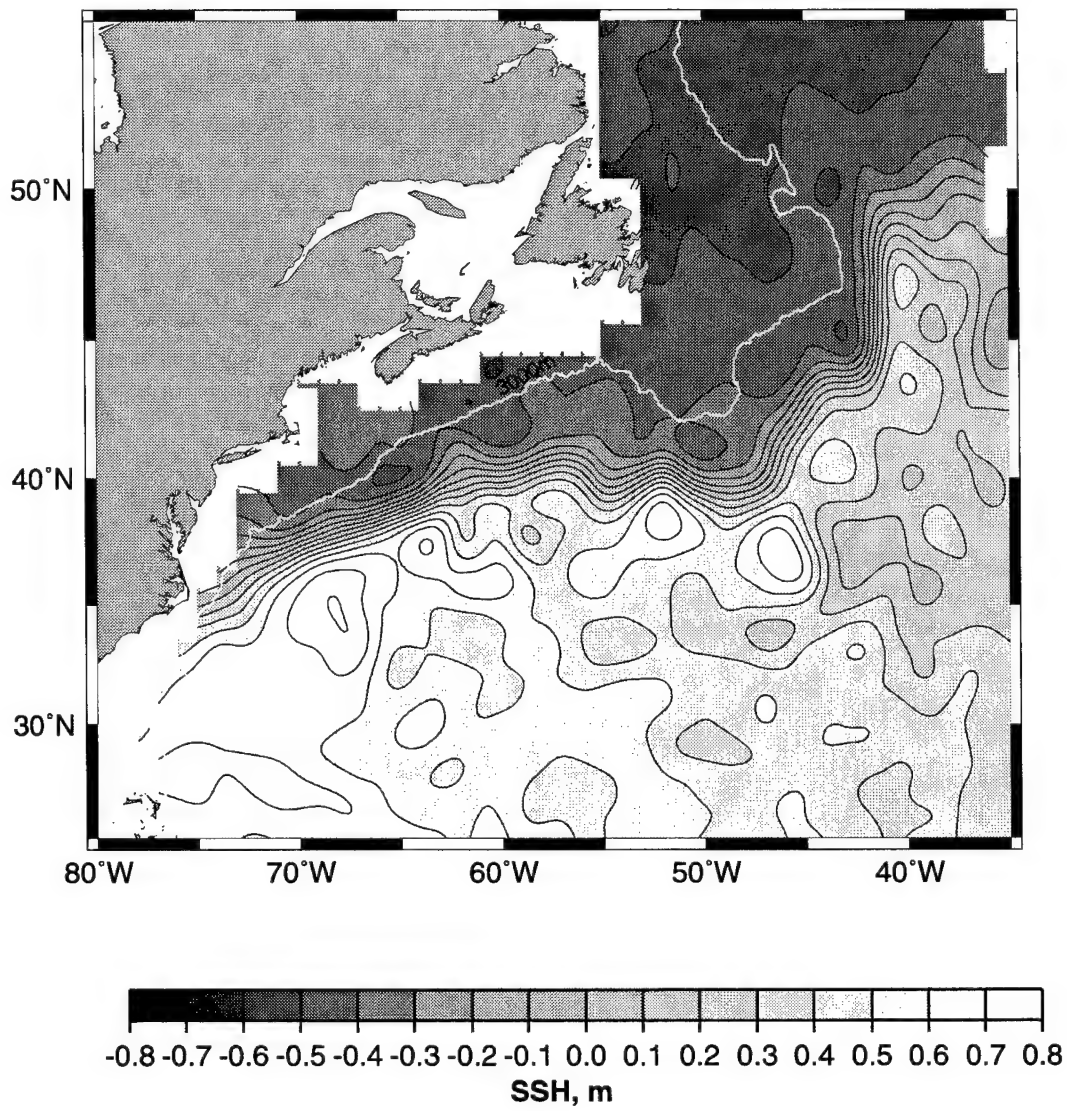


APPENDIX

July 93

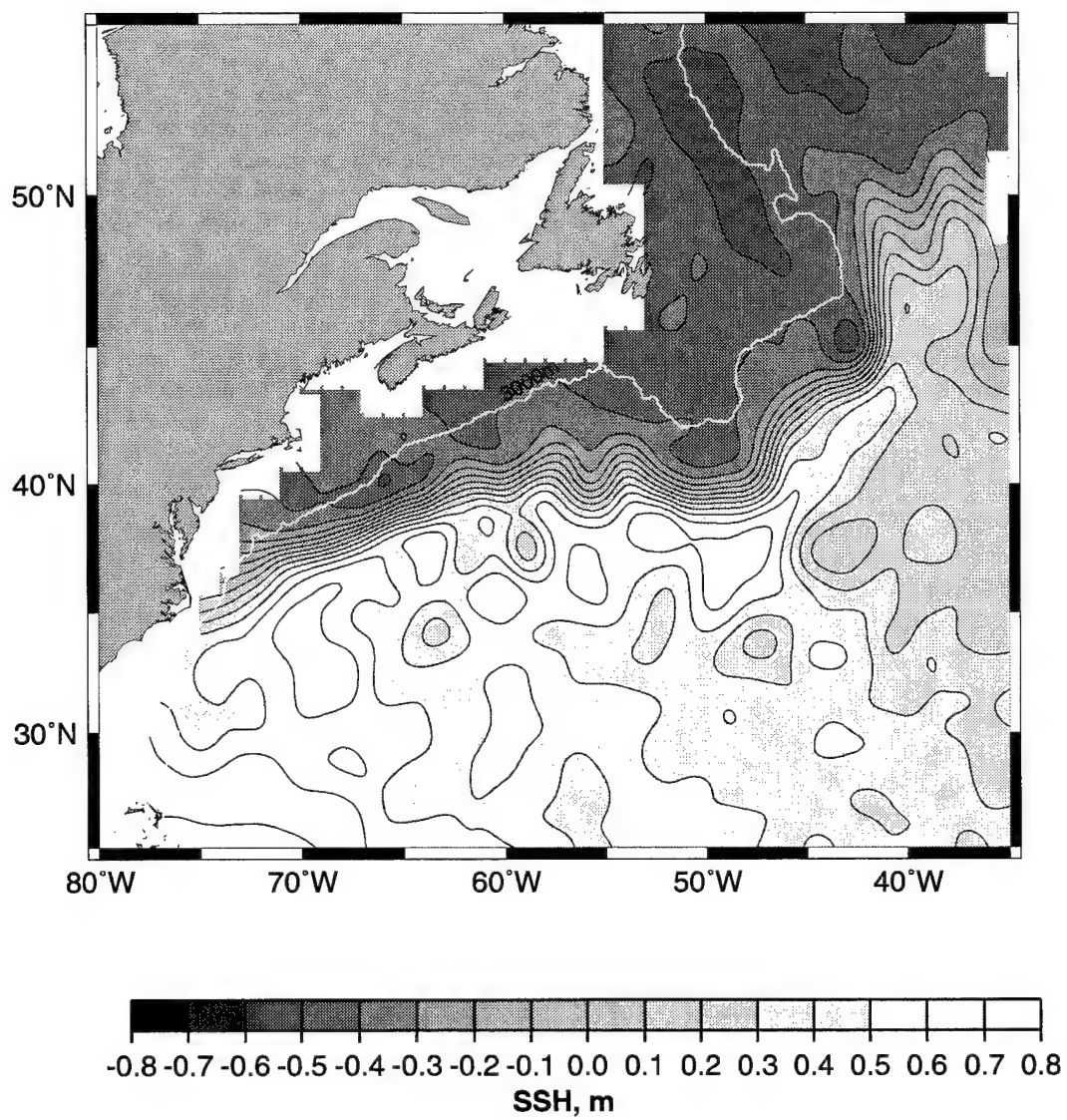


August 93

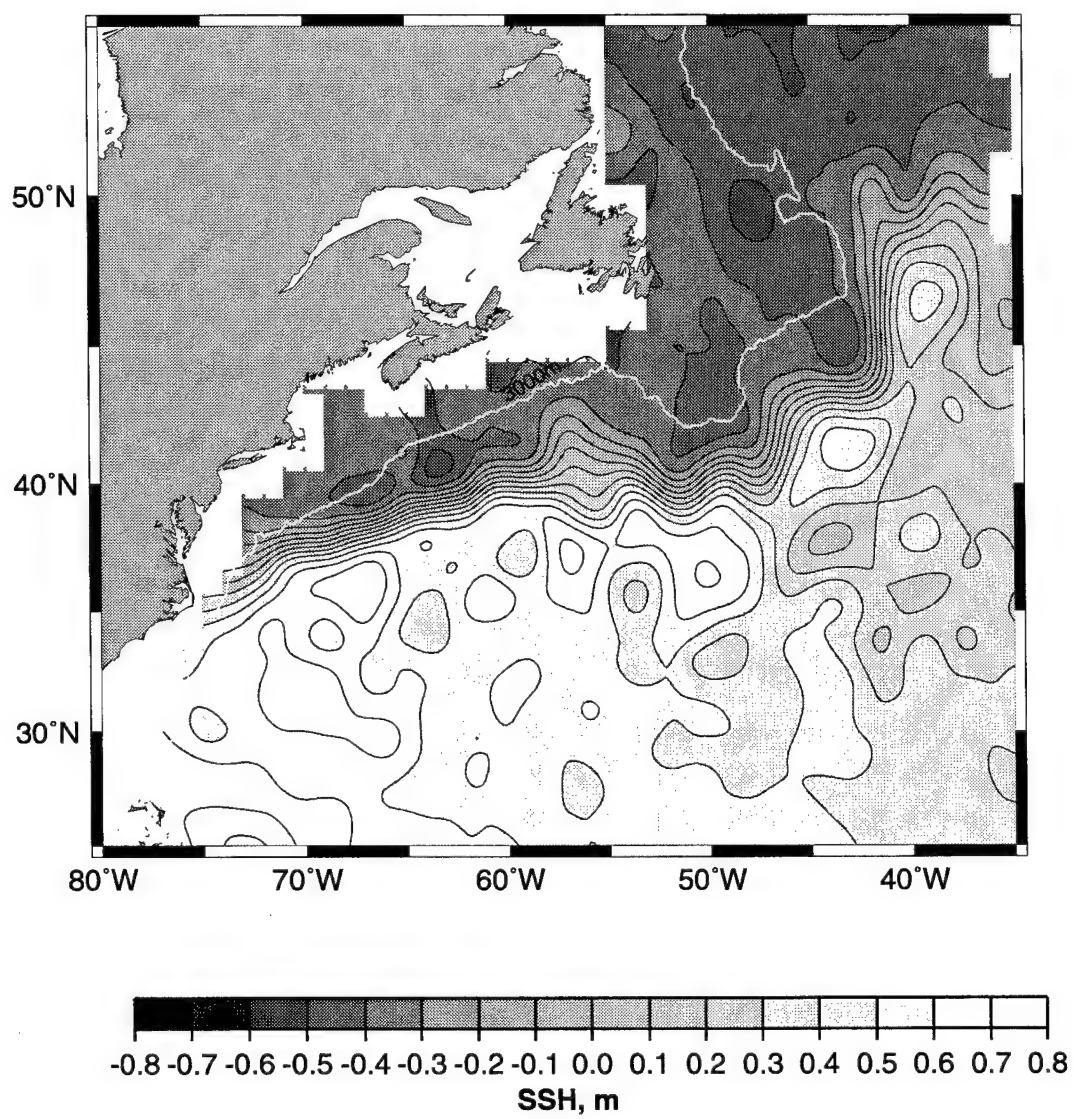


APPENDIX

September 93

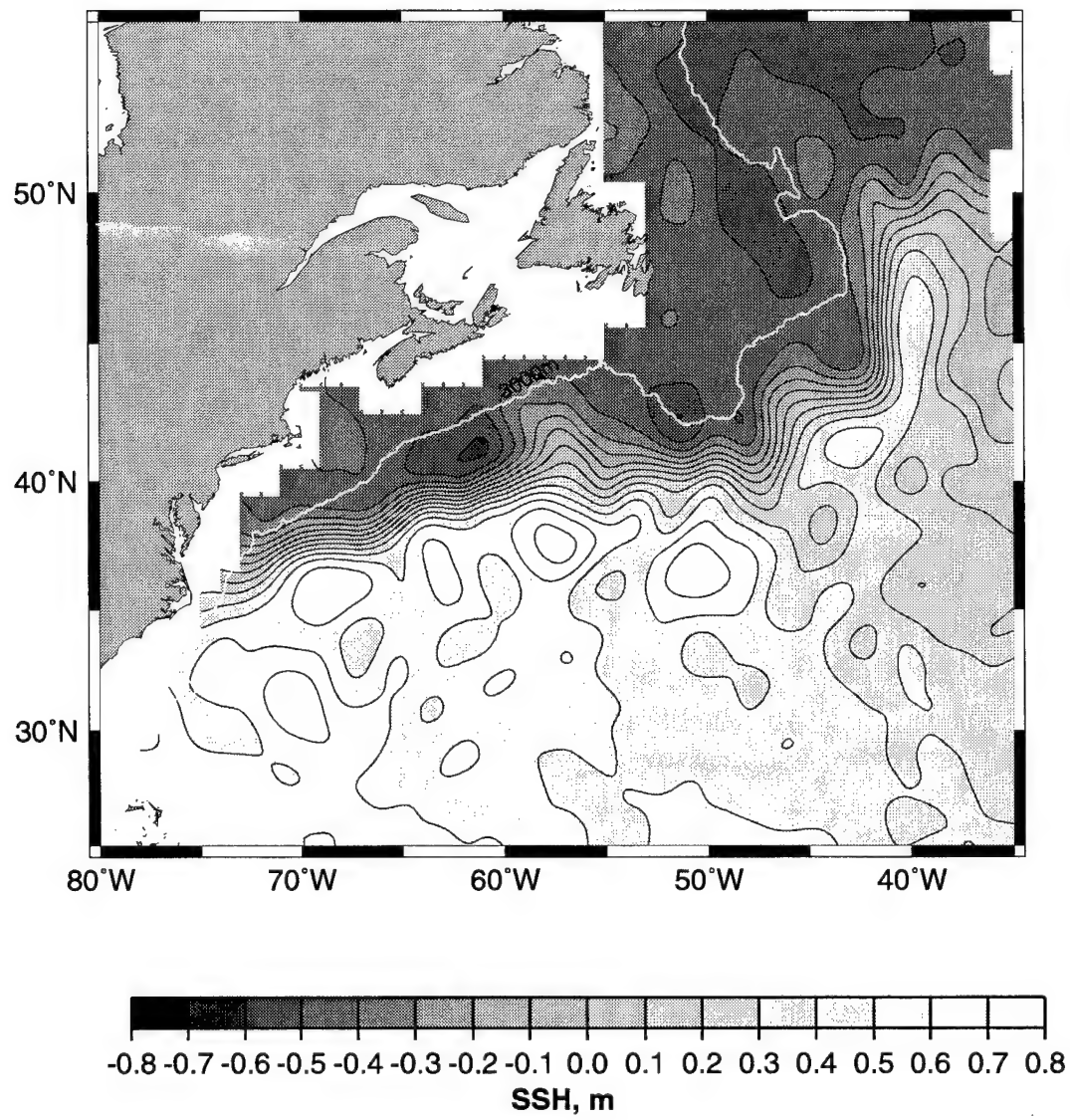


October 93

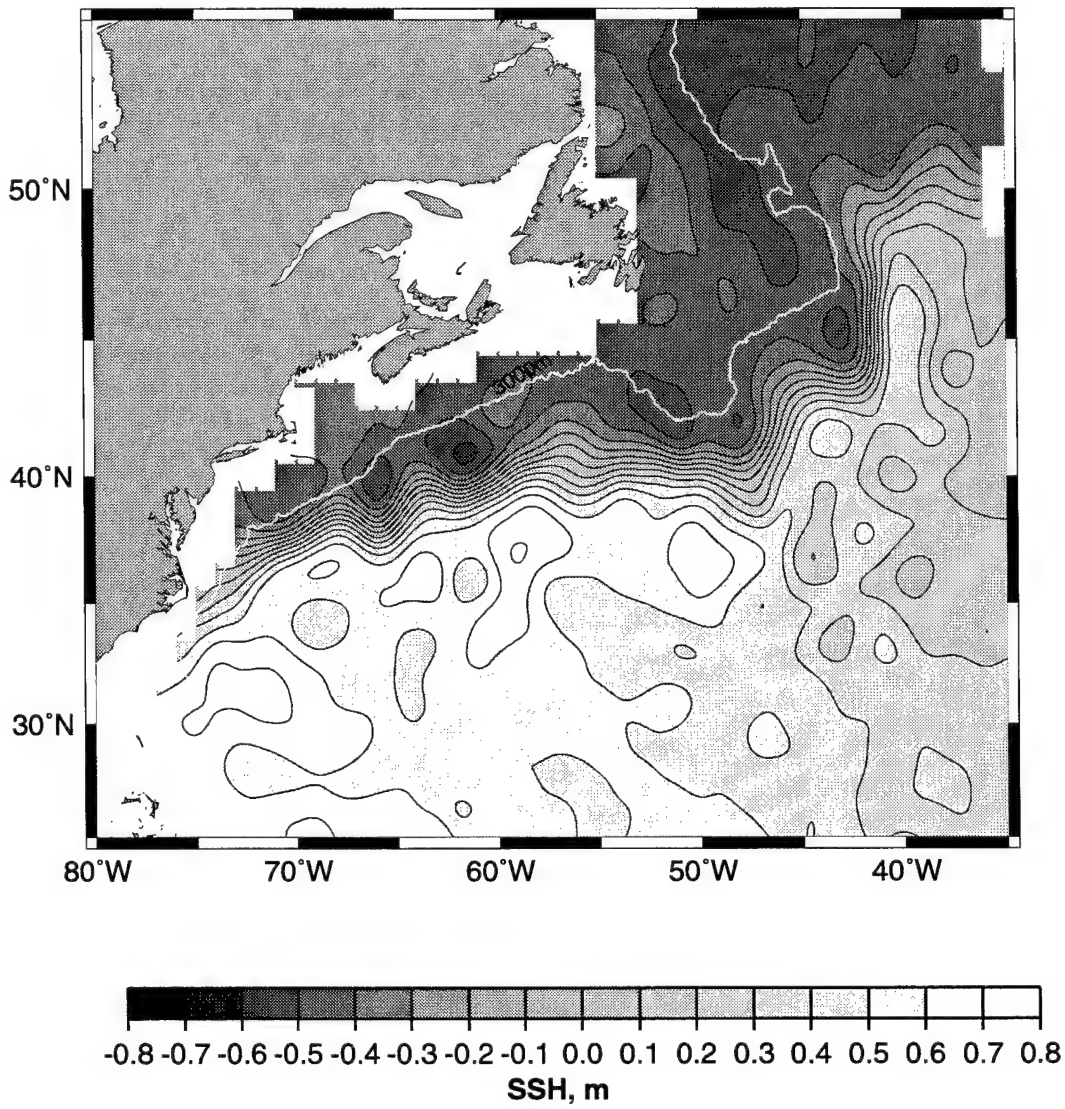


APPENDIX

November 93

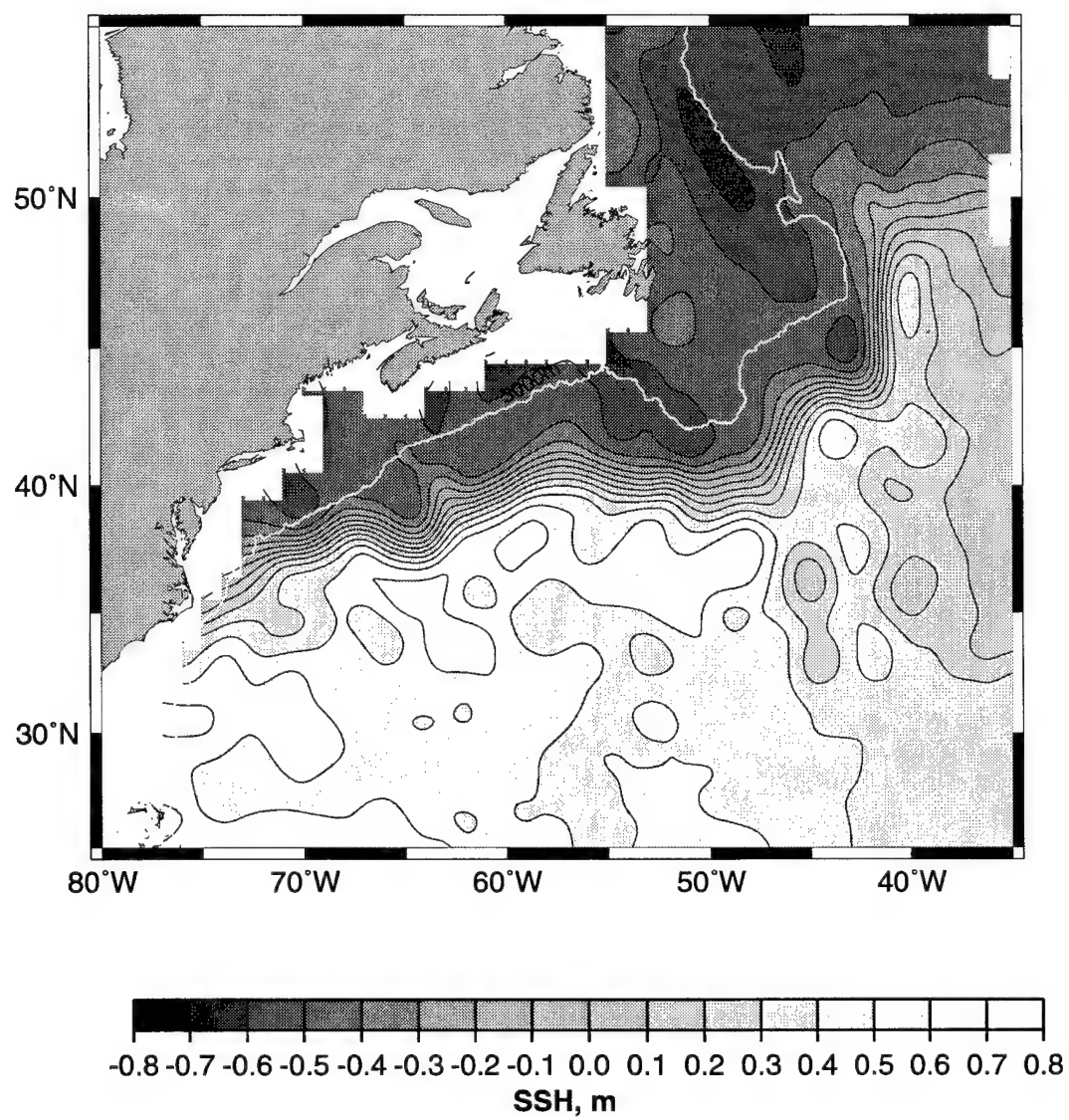


December 93

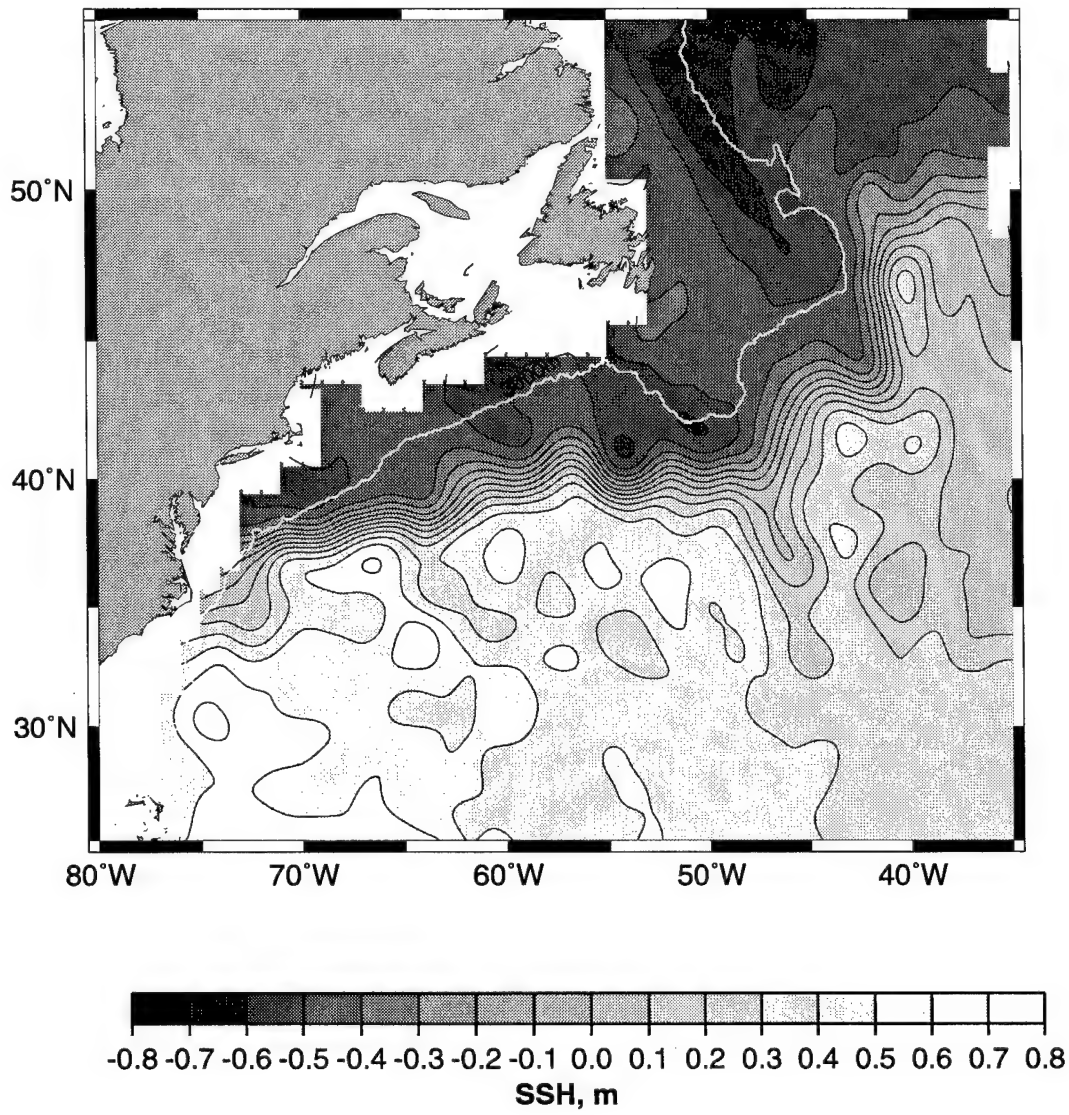


APPENDIX

January 94

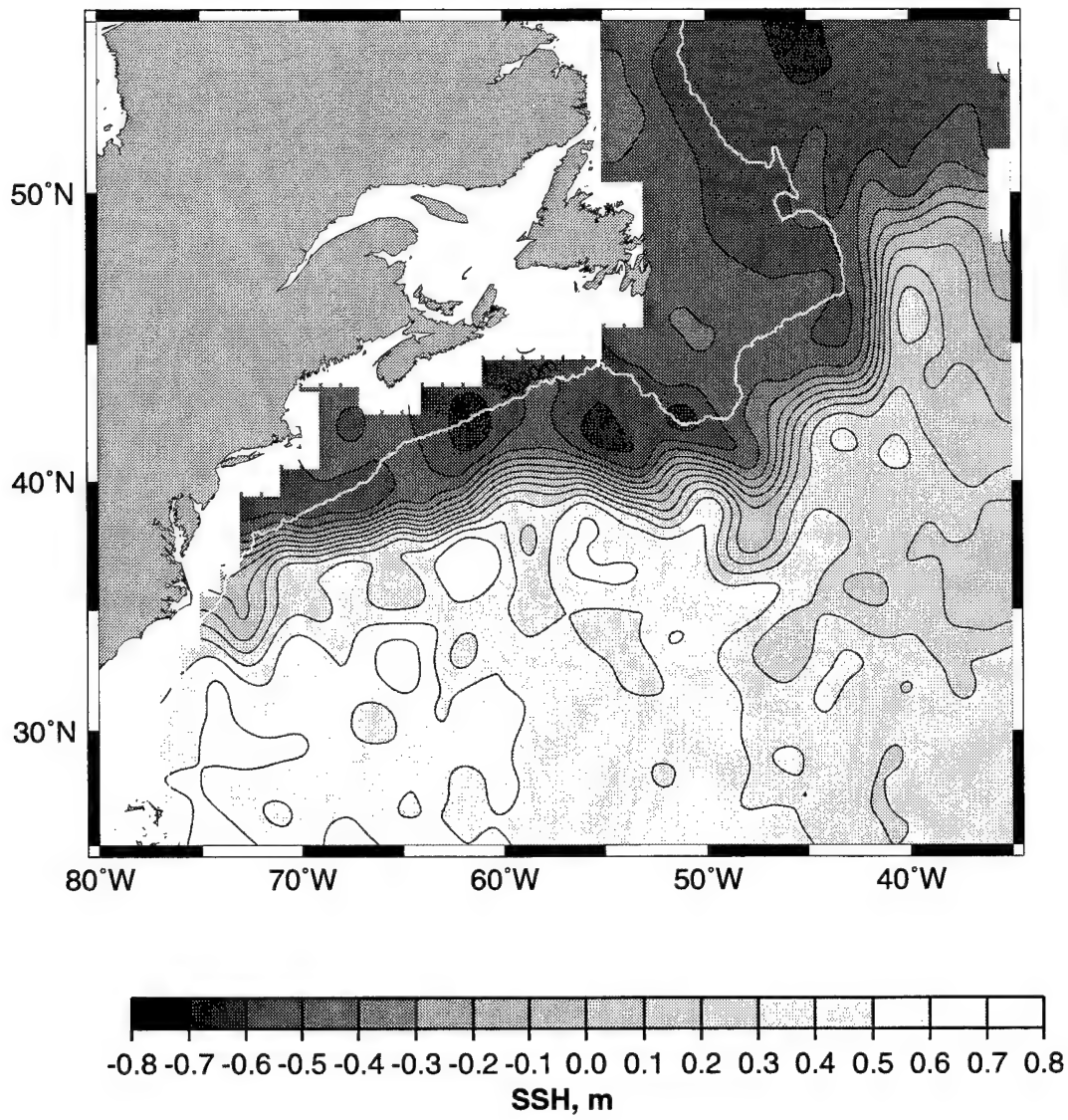


February 94

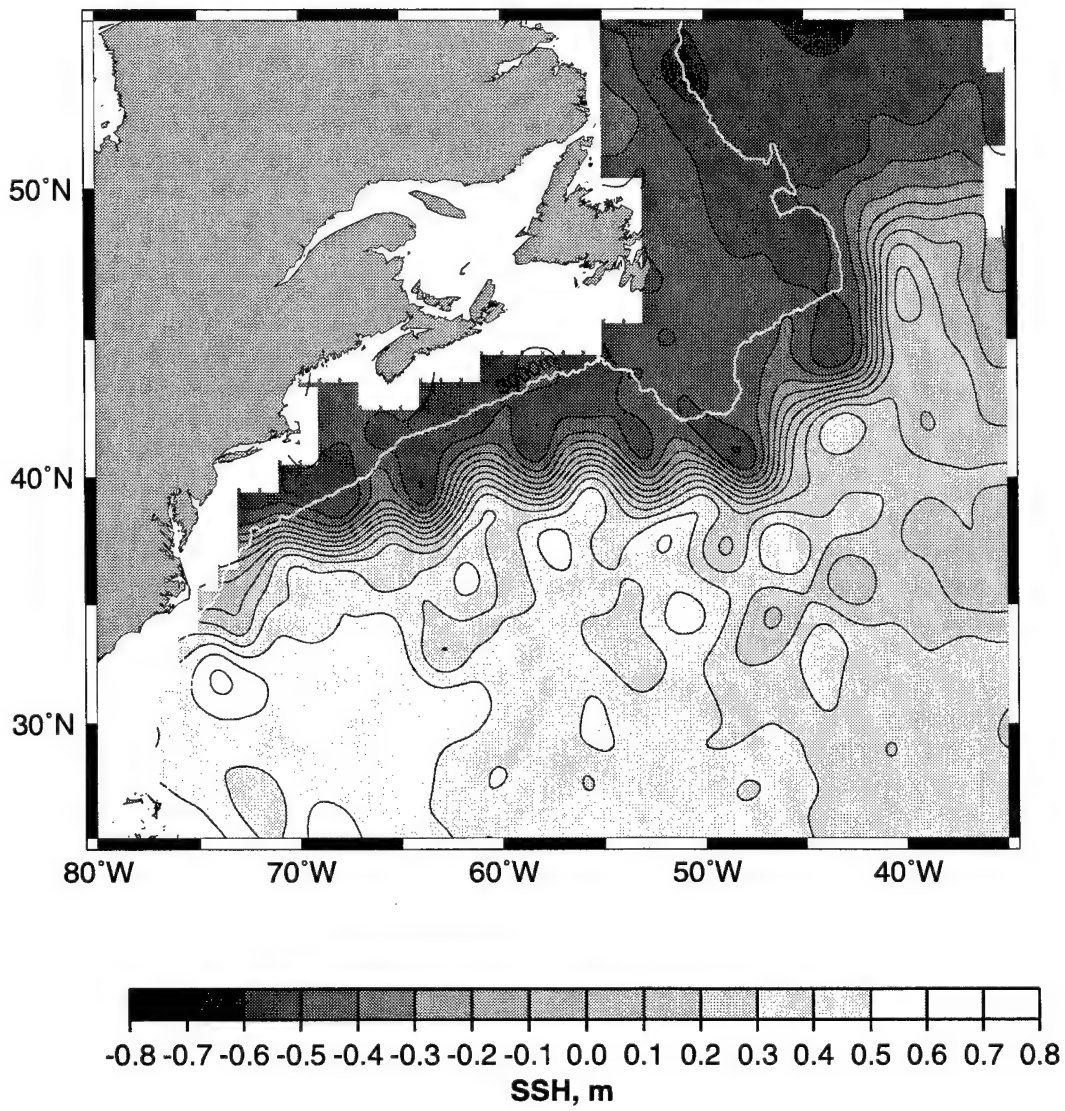


APPENDIX

March 94

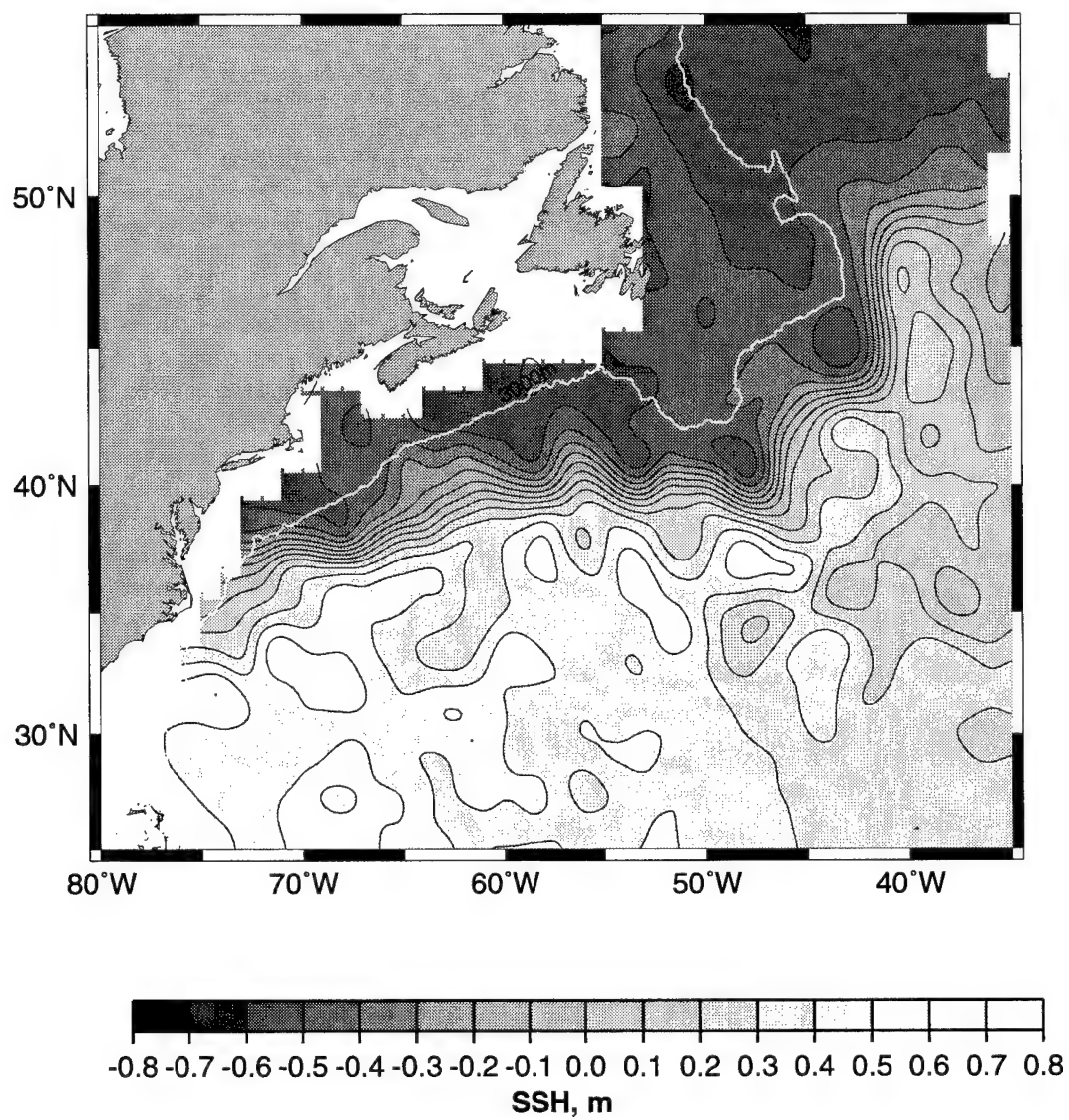


April 94

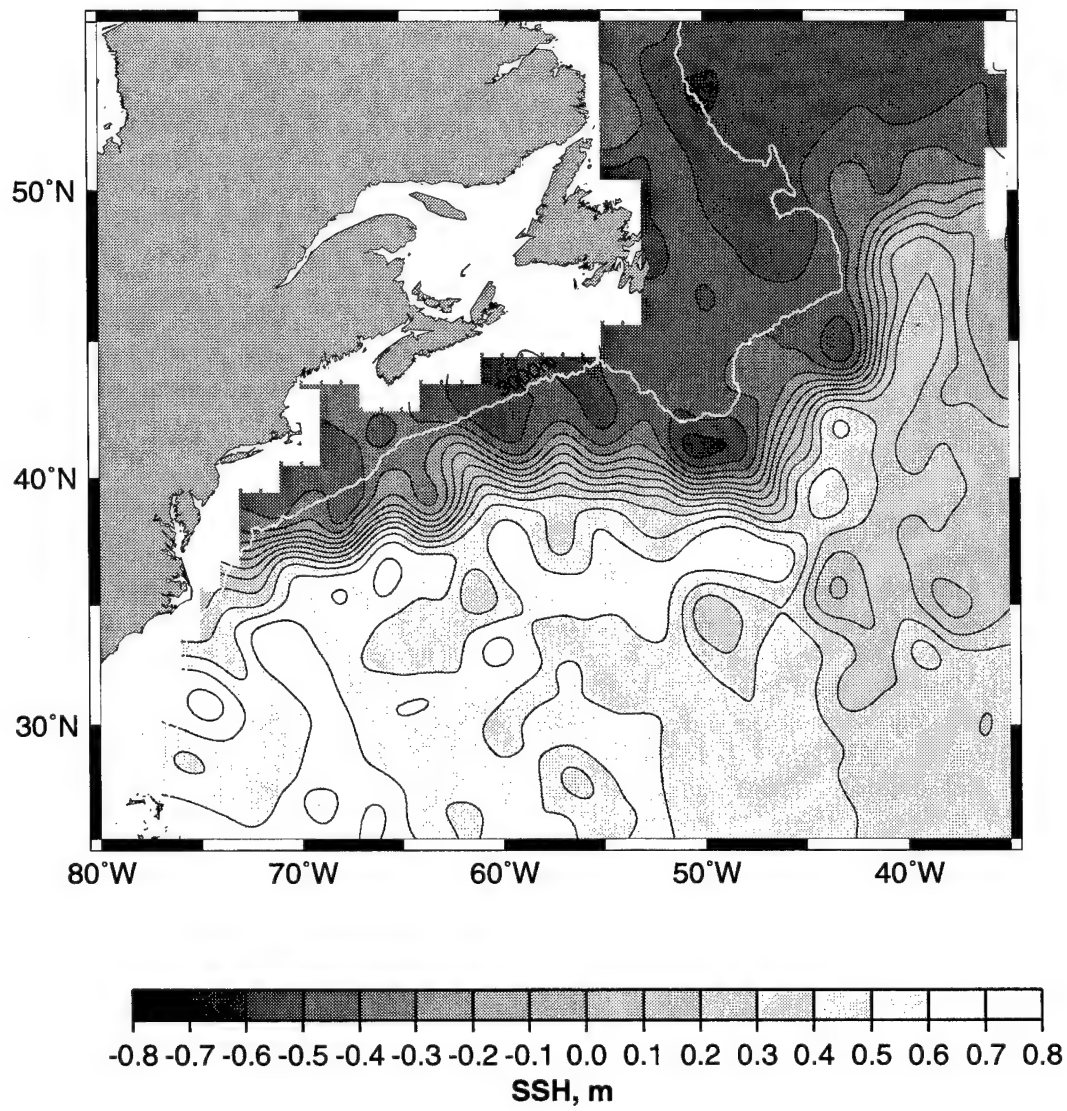


APPENDIX

May 94

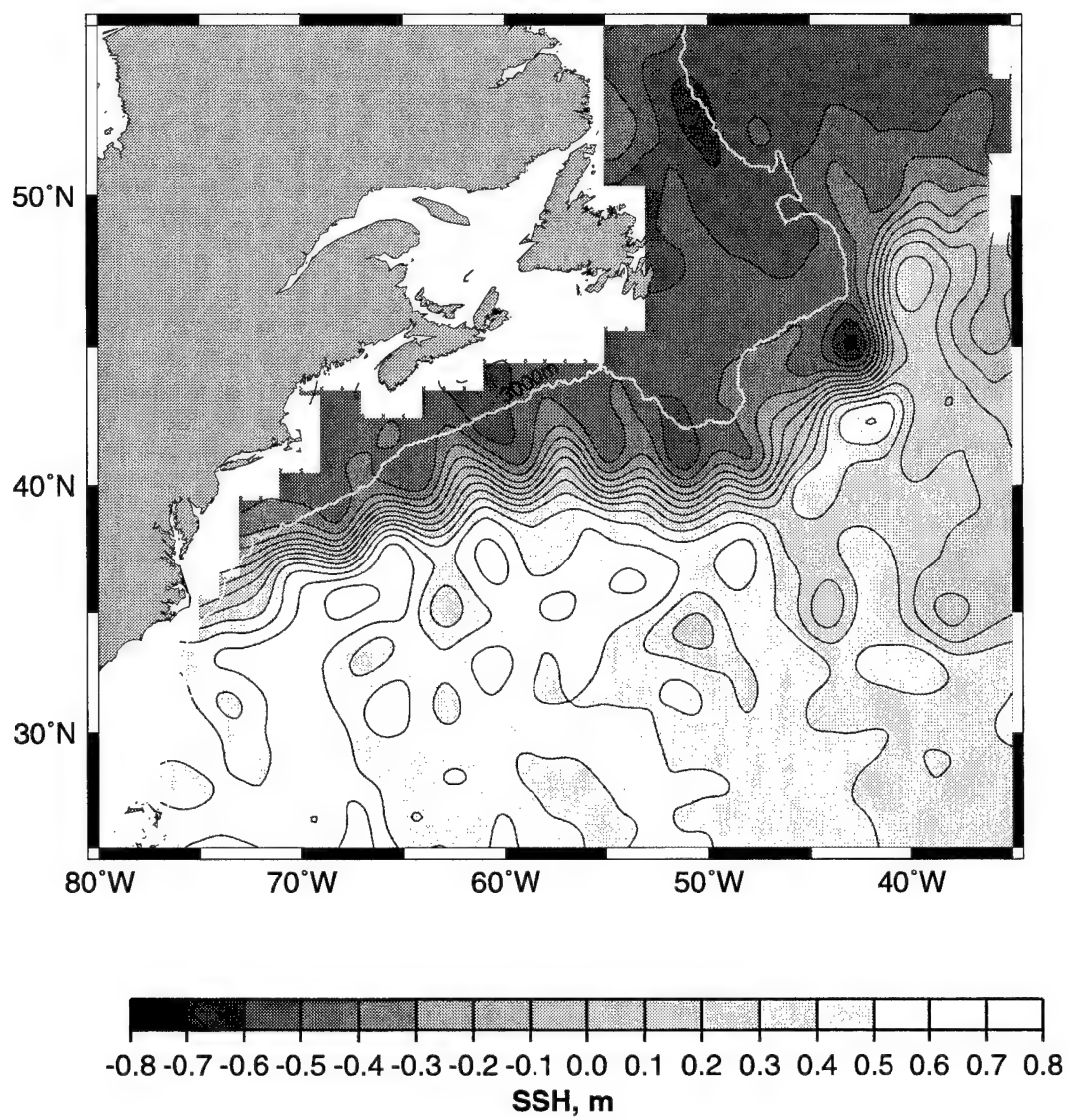


June 94

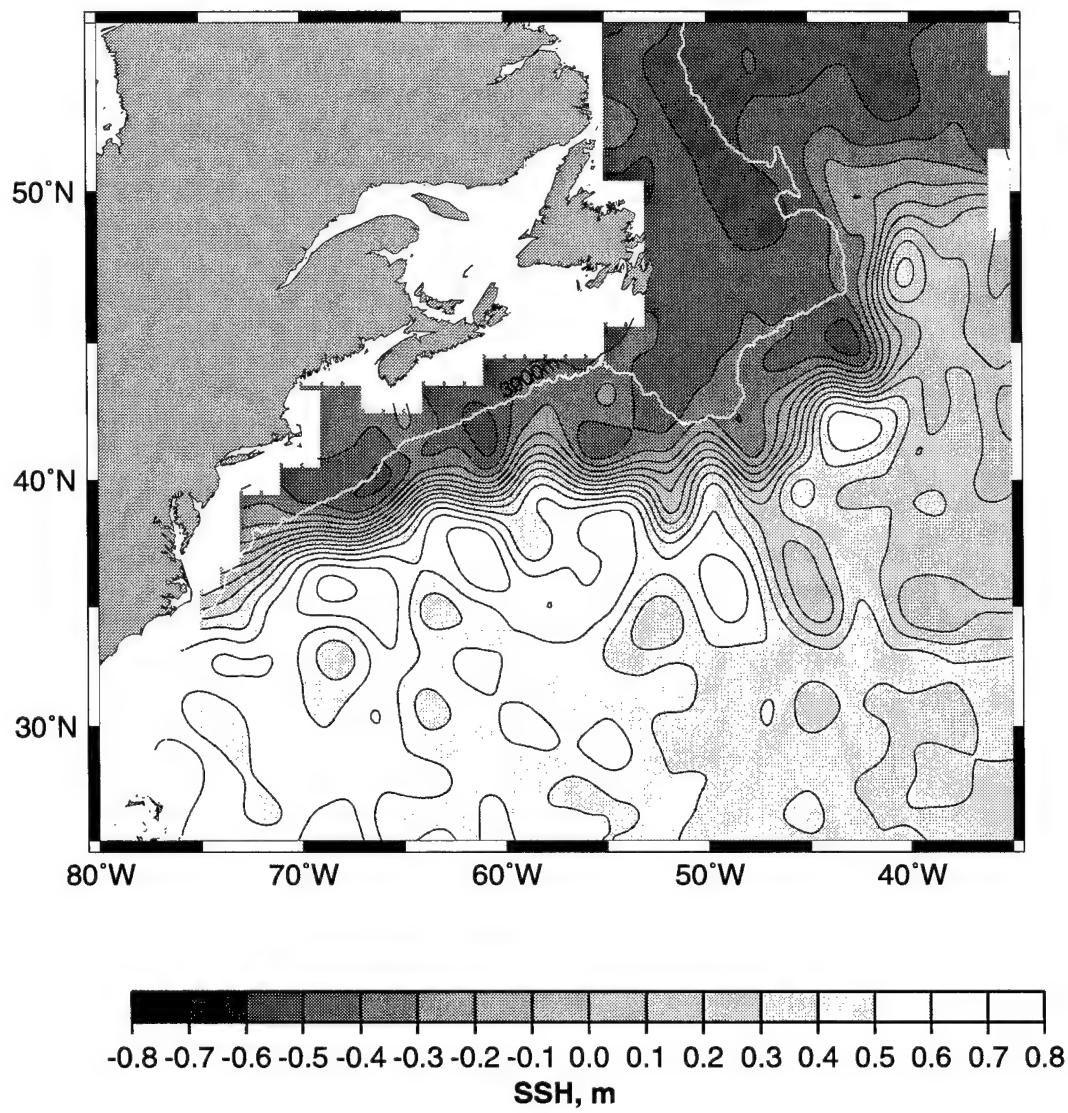


APPENDIX

July 94

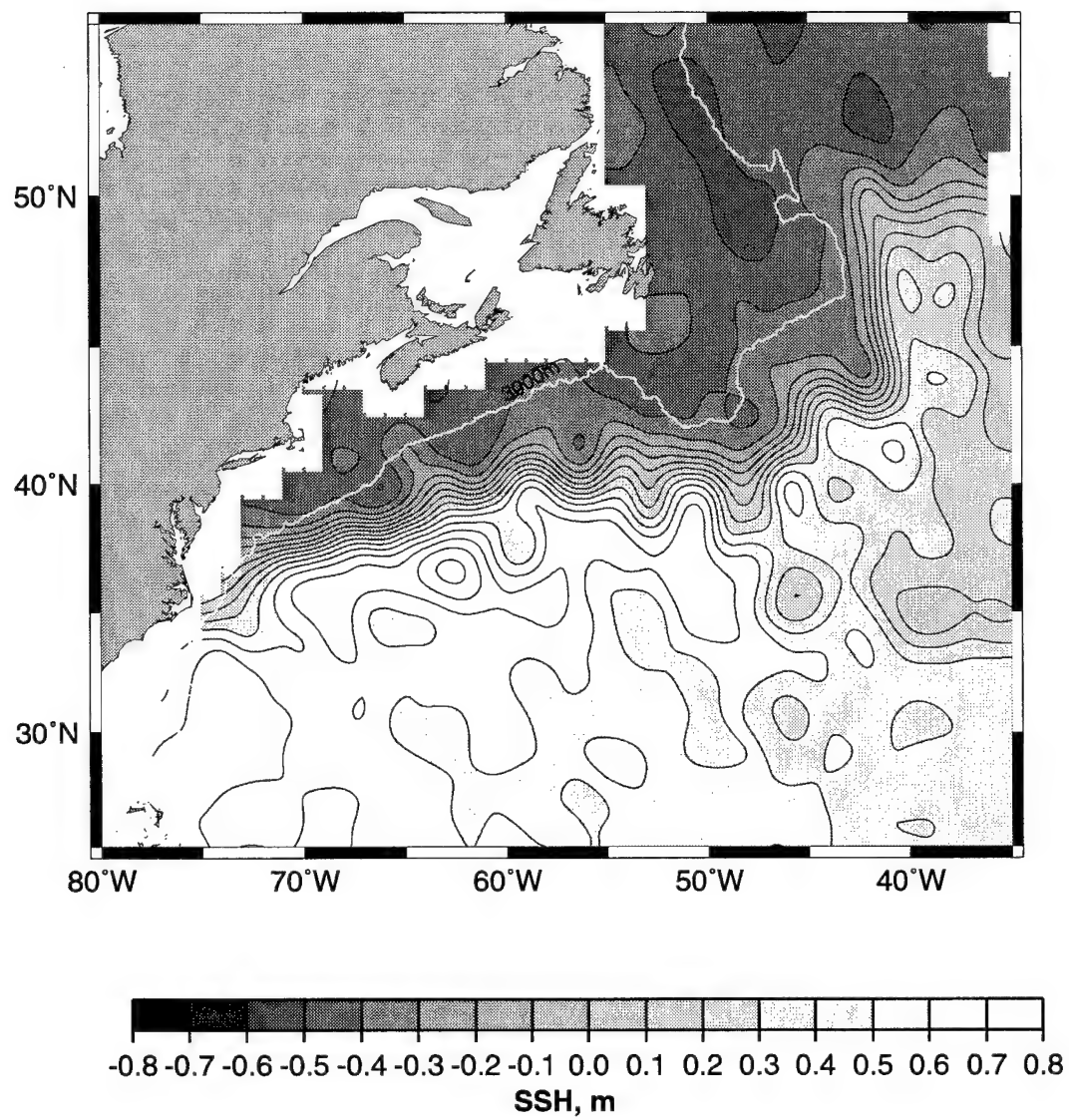


August 94

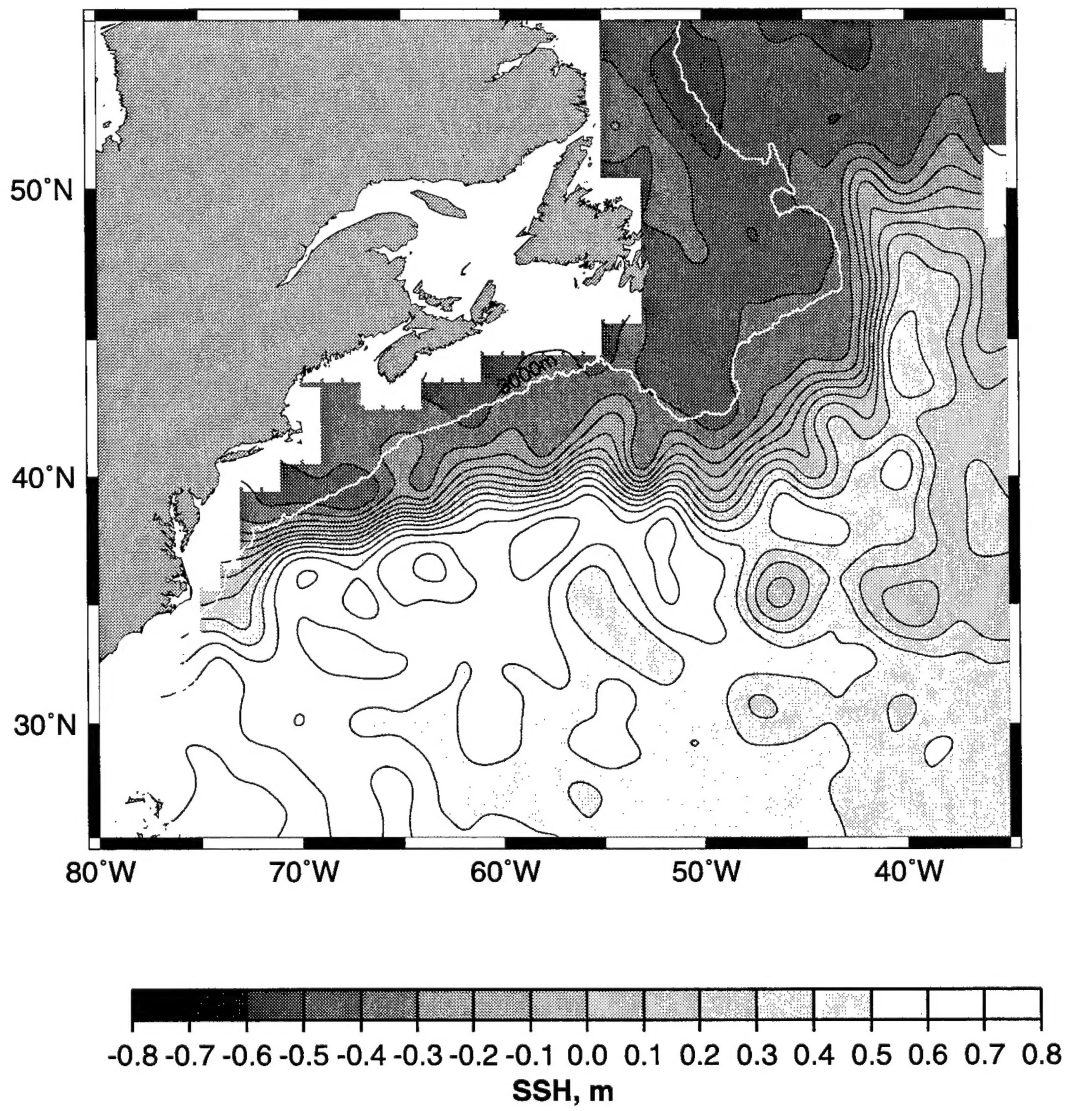


APPENDIX

September 94

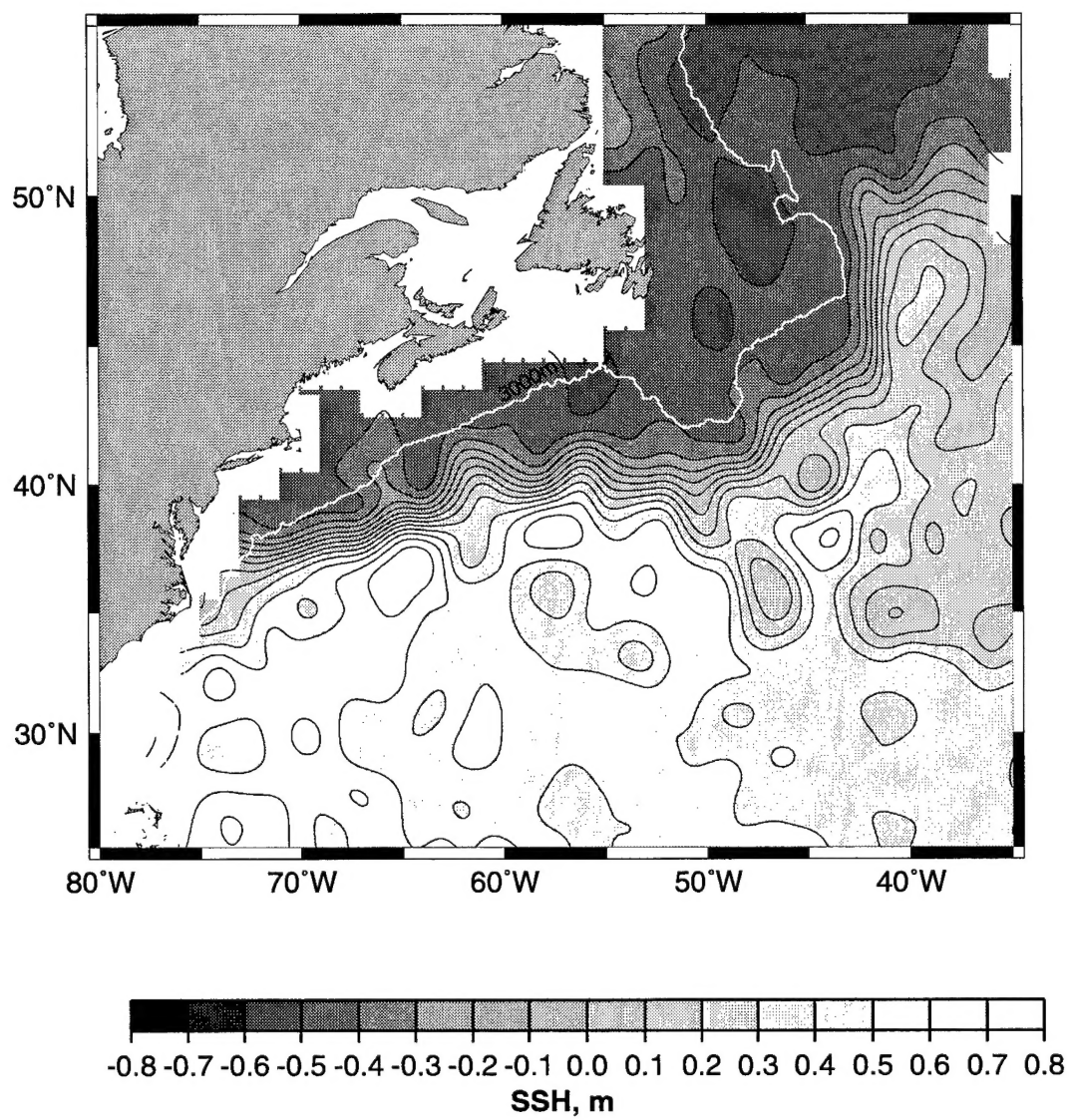


October 94



APPENDIX

November 94



DOCUMENT LIBRARY

Distribution List for Technical Report Exchange – February 1996

University of California, San Diego
SIO Library 0175C
9500 Gilman Drive
La Jolla, CA 92093-0175

Hancock Library of Biology & Oceanography
Alan Hancock Laboratory
University of Southern California
University Park
Los Angeles, CA 90089-0371

Gifts & Exchanges
Library
Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, NS, B2Y 4A2, CANADA

Commander
International Ice Patrol
1082 Shennecossett Road
Groton, CT 06340-6095

NOAA/EDIS Miami Library Center
4301 Rickenbacker Causeway
Miami, FL 33149

Research Library
U.S. Army Corps of Engineers
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Institute of Geophysics
University of Hawaii
Library Room 252
2525 Correa Road
Honolulu, HI 96822

Marine Resources Information Center
Building E38-320
MIT
Cambridge, MA 02139

Library
Lamont-Doherty Geological Observatory
Columbia University
Palisades, NY 10964

Library
Serials Department
Oregon State University
Corvallis, OR 97331

Pell Marine Science Library
University of Rhode Island
Narragansett Bay Campus
Narragansett, RI 02882

Working Collection
Texas A&M University
Dept. of Oceanography
College Station, TX 77843

Fisheries-Oceanography Library
151 Oceanography Teaching Bldg.
University of Washington
Seattle, WA 98195

Library
R.S.M.A.S.
University of Miami
4600 Rickenbacker Causeway
Miami, FL 33149

Maury Oceanographic Library
Naval Oceanographic Office
Building 1003 South
1002 Balch Blvd.
Stennis Space Center, MS, 39522-5001

Library
Institute of Ocean Sciences
P.O. Box 6000
Sidney, B.C. V8L 4B2
CANADA

National Oceanographic Library
Southampton Oceanography Centre
European Way
Southampton SO14 3ZH
UK

The Librarian
CSIRO Marine Laboratories
G.P.O. Box 1538
Hobart, Tasmania
AUSTRALIA 7001

Library
Proudman Oceanographic Laboratory
Bidston Observatory
Birkenhead
Merseyside L43 7 RA
UNITED KINGDOM

IFREMER
Centre de Brest
Service Documentation - Publications
BP 70 29280 PLOUZANE
FRANCE

REPORT DOCUMENTATION PAGE	1. REPORT NO. WHOI-97-06	2.	3. Recipient's Accession No.
4. Title and Subtitle Monthly Maps of Sea Surface Height in the North Atlantic and Zonal Indices for the Gulf Stream Using TOPEX/Poseidon Altimeter Data			5. Report Date June 1997
			6.
7. Author(s) Sandipa Singh and Kathryn A. Kelly			8. Performing Organization Rept. No. WHOI-97-06
9. Performing Organization Name and Address Woods Hole Oceanographic Institution Woods Hole, Massachusetts 02543			10. Project/Task/Work Unit No.
			11. Contract(C) or Grant(G) No. (C) NAGW-1666 (G) NAGW-4806
12. Sponsoring Organization Name and Address NASA			13. Type of Report & Period Covered Technical Report
			14.
15. Supplementary Notes This report should be cited as: Woods Hole Oceanog. Inst. Tech. Rept., WHOI-97-06.			
16. Abstract (Limit: 200 words) Monthly Maps of sea surface height are constructed for the North Atlantic Ocean using <i>TOPEX/Poseidon</i> altimeter data. Mean sea surface height is reconstructed using a weighted combination of historical, hydrographic data and a synthetic mean obtained by fitting a Gaussian model of the Gulf Stream jet to altimeter data. The resultant mean shows increased resolution over the hydrographic mean, and incorporates recirculation information that is absent in the synthetic mean. Monthly maps, obtained by adding the mean field to altimeter sea surface height residuals, are used to derive a set of zonal indices that describe the annual cycle of meandering as well as position and strength of the Gulf Stream.			
17. Document Analysis			
a. Descriptors altimeter Gulf Stream monthly maps			
b. Identifiers/Open-Ended Terms			
c. COSATI Field/Group			
18. Availability Statement Approved for public release; distribution unlimited.		19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 50
		20. Security Class (This Page)	22. Price